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Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey

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Cover:
Left: Photomicrograph of hydrogen-rich *Gloeocapsomorpha prisca* alginite typical of kukersite (potential hydrocarbon source rock) in Upper Ordovician Yeoman Formation, southeastern Saskatchewan (5-31-13-32W1, 1685.0 m). These algae were planktonic and benthic organisms, likely related to cyanobacteria. Image taken under fluorescent light; vertical field of view is 290 µm (courtesy of L.D. Stasiuk).
Right: Thin section photomicrograph of sphaerosiderite with opaque pyrite inclusions in a siliciclastic mudstone paleosol of the Late Albian Swan River Formation (from unit 1 of outcrop section 57 of McNeil and Caldwell (1981), Geol. Assoc. Can., Spec. Pap. 21, p350). Spherulitic structure shown by radial extinction patterns. The paleoenvironmental significance and stable isotopic signatures of sphaerosiderites in the Swan River Formation are discussed by White *et al.* in this volume. Cross-polarized light; vertical field of view is 0.65 mm (courtesy of T.S. White).

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Foreword

In this, the second issue of the Summary of Investigations, Volume 1, we present 12 papers that describe aspects of current geoscience research in Saskatchewan's Phanerozoic strata. All the projects are regional in their geographical coverage, which ranges from relatively restricted areas within Saskatchewan (e.g. Christopher, McNeil and Gilboy) to more global settings (e.g. Meyers and Sageman, Wagner). Many summarize research that might directly influence medium- and long-term oil and gas exploration strategy (e.g. Osadetz *et al*., Greggs and Hein, Seibel and Bend, Kreis and Kent, Ridgley). Others are academic in emphasis, their economic implications less direct and more dependent upon innovative interpretation and use by industry (e.g. Papadimitriou and Burden, White *et al*., Collom).

Researchers involved in the studies are based internationally (Australia, Eire, Israel, U.S.A.) and Canada-wide (Alberta, Newfoundland, Ontario, Saskatchewan). They represent the Canadian, U.S., and Saskatchewan governments as well as academia and industry, and bring much expertise and experience to help unravel the geological complexities of the province.

The hydrocarbon industry is of great importance to government and people of Saskatchewan, generating both direct revenues in the form of royalties and land sales, and high employment. In return, the government has long recognized its obligation to support the industry. Amongst the ways in which it accomplishes this are the maintenance of: i) a comprehensive well information system; ii) a highly functional core and drill-cuttings samples storage and examination facility; iii) appropriate geological expertise; and iv) publication of geological reports, maps and papers relevant to industry. All are extensively used by industry both for exploration and development, as well as by researchers, particularly postgraduate students. These data sources are readily available to anyone who is interested. I encourage their increased usage by explorationists and researchers alike, and suggest that serious consideration be given to publishing resulting geoscientific information in future issues of the Summary of Investigations, Volume 1.

An exciting development on the oil-industry scene in Saskatchewan is the establishment of the Petroleum Technology Research Centre (PTRC) in the University of Regina's Research Park. Whilst the centre is largely focused on engineering aspects of enhanced oil recovery, the fundamental importance of geoscience to the successful implementation of enhanced oil recovery techniques is fully recognized and relevant research is expected to increase. The largest of the early PTRC initiatives is the four-year, multi-national, multi-disciplinary Weyburn CO_2 Monitoring Project. The intent of this project is to study in great detail the local and regional movement of the large amounts of CO_2 that PanCanadian will be injecting into the Mississippian reservoirs in the Weyburn pool to enhance oil recovery by a CO_2 miscible flood. Such study should permit evaluation of the potential for long-term CO_2 sequestration in carbonate strata. Saskatchewan Energy and Mines plans to be involved in this research through the Petroleum Geology Branch, and to publish many of the findings in Volume 1 over the next several years.

G.C. Patterson
Executive Director
Exploration and Geological Services

April 2000

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A. Contributed Papers

Clues to the Origin, Tectonics, and Hydrocarbon Generation History of the Williston Basin from Apatite Fission Track Thermochronology

K.G. Osadetz [1], B.P. Kohn [2], S. Feinstein [3], and P.B. O'Sullivan [2]

Osadetz, K.G., Kohn, B.P., Feinstein, S., and O'Sullivan, P.B. (2000): Clues to the origin, tectonics, and hydrocarbon generation history of the Williston Basin from apatite fission track thermochronology; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

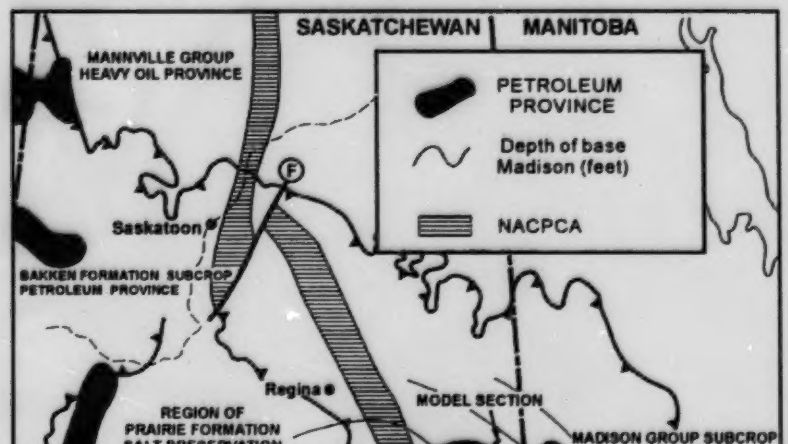
SASKATCHEWAN
MANITOBA
MANNVILLE GROUP HEAVY OIL PROVINCE
PETROLEUM PROVINCE
Depth of base Madison (feet)
NACPCA
F
Saskatoon
BAKKEN FORMATION SUBCROP PETROLEUM PROVINCE
Regina
REGION OF PRAIRIE FORMATION SALT PRESERVATION
MODEL SECTION
MADISON GROUP SUBCROP PETROLEUM PROVINCE
Missouri River
POPLAR DOME
NESSON ANTICLINE PETROLEUM PROVINCE
NORTH AMERICAN CENTRAL PLAINS CONDUCTIVITY ANOMALY
7000
F
5000
Bismarck
CEDAR CREEK ANTICLINE PETROLEUM PROVINCE
NORTH DAKOTA
SOUTH DAKOTA
3000
MONTANA
WYOMING
0
200 km

Figure 1 - Regional setting, major tectonic elements, and petroleum provinces of the Williston Basin. Basin form-lines are indicated diagrammatically over limited portions of the basin by the depth to the base of the Carboniferous Madison Group. F, inferred faults in the Precambrian basement.

1. Introduction

In this paper, the Williston Basin proper (Figure 1) is recognized as the sub-circular epicratonic Phanerozoic basin, approximately 800 km in diameter, that is located within the Williston Basin region, a more extensive area of Phanerozoic strata in Manitoba, Saskatchewan, and the adjacent USA (Gerhard *et al*., 1982). This distinction between the Williston Basin proper and the Williston Basin region reflects a stratigraphic continuity that extends well beyond the epicratonic basin (Burgess *et al*., 1997). The Williston Basin region overlies the Paleoproterozoic collisional Trans-Hudson Orogen, as well as the margins of the Archean Superior and Hearne/Wyoming cratons (Burwash *et al*., 1994; Leclair *et al*., 1997). It contains several significant petroleum provinces and mineral deposits which are randomly distributed both geographically and stratigraphically (e.g. Burrus *et al*., 1996).

Apatite fission-track (AFT) thermochronology and organic maturity data (Crowley *et al*., 1985; Crowley and Kuhlman, 1988; Kohn *et al*., 1995; Osadetz *et al*., 1998) indicate spatial and temporal variations in the thermal history of the Williston Basin and adjacent Precambrian Shield of North America (Figures 1 and 2). On the Canadian Shield and under areas of the Williston Basin region which have thin

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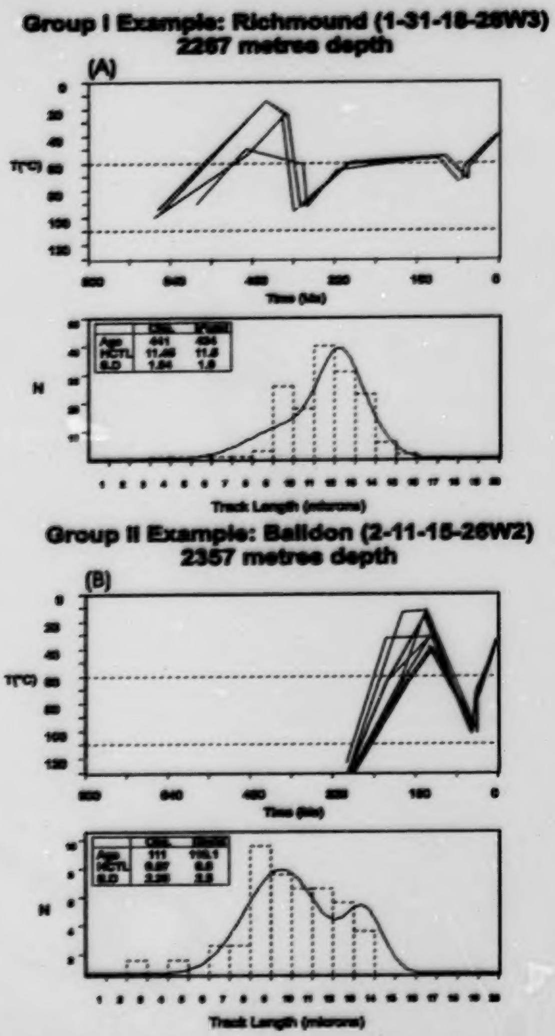

Figure 2 - Best match thermal history models for Group I (A), undisturbed exposed Shield or shallowly buried Williston Basin region, and Group II (B), deeply buried Williston Basin proper, samples as defined by Osadetz et al. *(1998). Models for Group I samples record regional late Precambrian cooling, whereas Group II models commence with Late Paleozoic cooling. Note the similarity of Mesozoic and Cenozoic thermal histories for both groups of samples.*

Phanerozoic cover, AFT data typically record late Precambrian cooling followed by intervals of Phanerozoic heating and cooling, the pattern of which mimics the Phanerozoic sedimentation history. Elsewhere, the earlier thermal history is overprinted by resetting of AFT clocks during the Late Paleozoic. The region affected by this Late Paleozoic thermal event includes both a broad portion of the "central basin", extending more than 300 km from the basin centre where the Phanerozoic succession is up to 5 km thick, and a linear zone, at shallower depths, stretching from the Williston to Athabasca basins (Figure 2). It thus broadly conforms to the area occupied by the Devonian Elk Point Basin.

2. Interpretation

Our analysis distinguishes the Late Paleozoic event extending into the Williston Basin region from the Early Paleozoic origin of the Williston Basin proper (Figures 3 and 4). We infer that the Williston Basin proper formed as the result of at least two distinct thermo-mechanical processes. Initial Ordovician-Silurian subsidence is generally contemporaneous with the initial subsidence of other North American intracratonic basins (Sloss, 1984). It has been attributed by Hamdani *et al.* (1994), Ahern and Mrkvicka (1984), and others to the thermal contraction of a large sill intruded into the lower crust. An upward migration of the lithosphere-asthenosphere boundary (LAB) in Devonian time provides a plausible mechanism for linking Late Paleozoic and Early Mesozoic tectonic events in the Williston Basin region. These events include accelerated Middle Devonian to Carboniferous subsidence, Late Paleozoic increase in basal heat flow, followed by Late Paleozoic to Early Mesozoic uplift and erosion. They were succeeded by Triassic and Jurassic subsidence signifying the decay of the heat flow anomaly. Whereas accelerated Devonian-Carboniferous subsidence and the Late Paleozoic thermal event took place in essentially the area of the Devonian Elk Point Basin, Early Mesozoic subsidence was restricted to that region where the Elk Point and Williston basins are superimposed. This restriction of Triassic-Jurassic subsidence to the region of the Williston Basin proper is inferred to indicate a mechanical response, probably a phase change, involving the igneous sill responsible for the initial Ordovician-Silurian subsidence of the Williston Basin.

We conclude that the accelerated Devonian-Carboniferous subsidence and the succeeding Late Paleozoic thermal event are both responses to thermal thinning of the continental lithosphere, temporally separated by the thermal inertia of the continental lithosphere. The differing response between areas within the Williston Basin proper, and those outside, may be due to the effects of Late Paleozoic heating on the intrusion inferred responsible for initiating Williston Basin subsidence in Early Paleozoic time (Ahern and Mrkvicka, 1984). Therefore the origin and pattern of Williston Basin subsidence is inferred to be episodic and fortuitous as opposed to continuous and discrete. Other epicratonic basins (e.g. Illinois Basin) exhibit either accelerated subsidence or thermal anomalies in Late Paleozoic time (e.g. Kominz and Bond, 1991). Together these may define a previously unrecognized, but widespread and coordinated interaction with the sublithospheric mantle. A final phase of subsidence contemporaneous with the formation of the Cretaceous-Paleogene Interior Seaway and Laramide Orogeny (Figure 3) may be due to other processes interacting with pre-existing lithospheric structure (Burgess *et al.*, 1997), but without a change in basal heat flow (Figure 4).

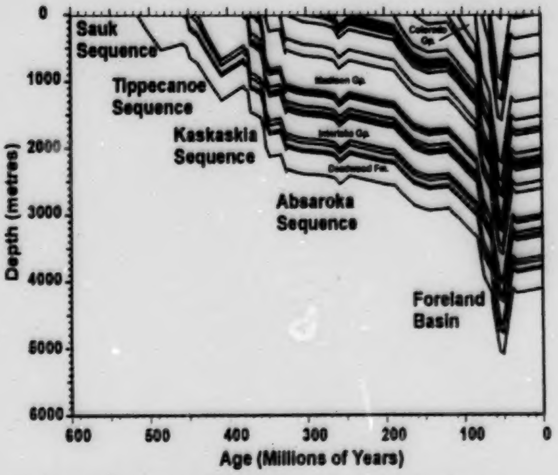

Figure 3 - Representative Williston Basin burial history model similar to that used to constrain thermal history models. Notice the acceleration of subsidence accompanying Kaskaskian and Foreland Basin sedimentation in the Late Paleozoic and Early Mesozoic, respectively. Comparison with Figure 2 indicates that the total resetting of AFT clocks during the Late Paleozoic precedes maximum burial in the Paleogene, a clear indication that basal heat flow was higher in the Late Paleozoic than in the Paleogene.

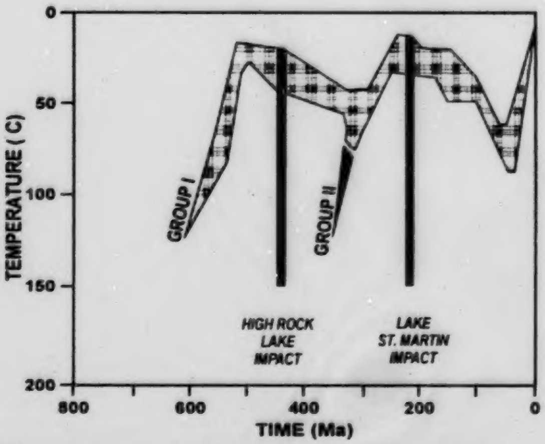

Figure 4 - Generalized thermal history models for Group I (undisturbed exposed Shield or shallowly buried Williston Basin region), Group II (deeply buried Williston Basin proper), and select Group III (High Rock Lake and Lake St. Martin impact crater samples generally restricted to the eastern limits of Williston Basin region, as defined by Kohn et al., 1995) sample locations. Group II is distinguished from Group I by the total resetting of AFT clocks in Late Paleozoic time. Notice that the subsequent history of Group II and Group III samples is similar to that of Group I samples during the Mesozoic and Cenozoic.

3. Implications for Petroleum Systems

The Late Paleozoic thermal event identified in this study has great significance for potential petroleum systems in the Sauk and Tippecanoe sequences, both of which reached the oil window for Type II organic matter at that time (Osadetz *et al.*, 1998). Within the region affected by the Late Paleozoic thermal event is a persistent region of elevated heat flows associated with crustal structure, specifically the North American Central Plains Conductivity Anomaly (NACPCA) and the Nesson Anticline (Majorowicz *et al.*, 1988; Figure 1). Along the Nesson Anticline, oil windows in Paleozoic strata occur 750 to 1250 m higher in comparison to other regions affected by the Late Paleozoic heating (Osadetz *et al.*, 1989). This persistent geographical heat flow variation is attributed to crustal compositional differences originating during the Precambrian Trans-Hudson Orogeny (Morel-a-l'Huissier *et al.*, 1990). Together these effects suggest early opportunities for hydrocarbon generation, migration and entrapment in the Williston Basin which are not indicated by analysis of the Devonian and Carboniferous petroleum systems alone (Osadetz *et al.*, 1998).

4. Acknowledgments

This study was supported by the Australian Research Council and the Australian Institute of Nuclear Science and Engineering and Geological Survey of Canada Project 950003. Manitoba Energy and Mines staff and Saskatchewan Energy and Mines staff, especially Dr. D.F. Paterson (retired) and Ms. F.M. Haidl, facilitated the collection of basement samples from petroleum boreholes.

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The Sedimentology and Structure of the Lower Paleozoic Deadwood Formation of Saskatchewan

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Greggs, D.H. and Hein, F.J. (2000): The sedimentology and structure of the Lower Paleozoic Deadwood Formation of Saskatchewan; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

1. Introduction

Strata of the Deadwood Formation provide the first record of a marine incursion over the areas now known as the Williston Basin and the Western Canada Sedimentary Basin. Although their preservation appears to be limited to within these basins, which both formed after Deadwood time, the sediments from which they developed probably covered a much broader area. The Deadwood Formation is a mixed clastic-carbonate succession dated as Late Cambrian to Early Ordovician in the Williston Basin (Lochman-Balk and Wilson, 1967) and as Late Cambrian to possibly Early Ordovician in the Alberta subsurface (Hein and Nowlan, 1998). Additional Saskatchewan conodont data are available in Nowlan (1999, 2000). A review of dating and correlation work on these rocks for Western Canada (Aitken, 1997; Pugh, 1970) and for North Dakota and South Dakota (location of the type section) suggests firm evidence of a Middle Cambrian age for the lower portion of this succession is lacking. The usage of "Earlie Formation" for this lower portion is therefore discontinued (Greggs, unpubl. data), and, throughout this paper, the Deadwood Formation comprises the entire interval from the top Precambrian to the unconformity at the top of the Deadwood. A similar revision was proposed by Hein and Nowlan (1998) for use in the subsurface of eastern Alberta where separating the Earlie from the Deadwood is difficult.

The focus of this paper is to integrate Deadwood sedimentology, as documented through core examination, with basement structure and reactivation (this forms the basis for Gregg's M.Sc. thesis). A further report will be submitted for the Summary of Investigations 2001.

2. Sedimentology

Saskatchewan data were compiled from 30 Deadwood cores examined by Greggs and eight cores logged by Hein and Nowlan (unpubl.). Generally, Saskatchewan cores are much longer and more continuous through the Deadwood interval than their Alberta counterparts, facilitating the development of a typical lithological profile. In ascending order, the typical lithofacies are:

1) Precambrian granites or gneisses: commonly fractured.
2) Precambrian regolith: red and green, chloritic, granular feldspathic arenites, commonly with large Precambrian pebbles or boulders (>core diameter); commonly fractured.
3) Granular sandstones: red and white arkosic and quartzitic sandstones, granular to very coarse and coarse, cross-bedded, interbedded with finer or argillaceous laminae; porosities fair to moderate.
4) Quartz arenites: cream, greenish, tan and/or pink; dominantly very clean quartz sandstones, some kaolinitic; overall fining-upward from coarse to medium to fine and very fine grain sizes. Several 1 to 1.5 m thick, fining-upward cycles may be present within any one well. These sandstones are typically glauconitic (marine), and the coarser intervals may be hematitic. Porosities range from poor to very good; most sandstones are at least moderately porous. Several cores recovered very poorly indurated sands, suggesting that high initial intergranular porosities coupled with fracturing resulted in little functional cementation.

   Depositional facies are variable: finer grained sediments show distinct burrows and bioturbation, medium-grained sediments are more likely to retain trough and planar cross-bedding; coarser grained layers generally appear almost massive, with crossbeds only vaguely visible. Green argillaceous partings or fine laminae may cap the small cycles or be interbedded with the sandstones.
5) Siltstone-shales: generally buff, greenish, and/or maroon (shales), laminated, burrowed, rarely calcareous.
6) Argillaceous limestones and shales: dark grey or black, silty, commonly with minor sandstone interbeds; may contain brachiopod fragments or conodonts. Shales may be fissile and platy; often with disseminated pyrite; may also be calcareous.
7) Flat-pebble conglomerates: vari-coloured, elongate, internally laminated pebbles which may

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have glauconitic rims, in a finer grained matrix; scour surfaces common at contact with underlying beds. These conglomerates are found in the upper part of the Deadwood, commonly near the top of the unit and interbedded with fine sandstones and siltstones or limy units.

The Deadwood sandstones of Saskatchewan are non-garnetiferous in contrast to those of North Dakota, which contain abundant garnets. This is simply a result of provenance: the Precambrian of North Dakota is commonly a garnetiferous schist whereas in Saskatchewan the Deadwood overlies granites and gneisses. Petrographic work on some of the Saskatchewan cores revealed rare and tiny garnets as accessories and, more commonly, zircons and strained quartz.

The general environment of deposition is considered to have been a shallow epeiric sea, as reported by other workers. The shallow marine environments comprise mainly foreshore (inter-tidal) to shoreface. Little evidence has been preserved to show that water depths were greater than about 20 m (i.e. several metres below fair weather wave base). *Skolithos*, a common ichnofossil, is indicative of the middle and upper shoreface of sandy shorelines. *Planolites* and a few *Diplocraterion* burrows were also identified. Their presence is consistent with an upper shoreface interpretation (Pemberton *et al.*, 1992).

Eustatic sea-level changes are suggested by the fining-upward cycles and lithological breaks, which are common throughout the Deadwood clastics.

3. Basement Structure and Lineament Analysis: Previous Work

a) U.S. Williston Basin

Structural controls on the southern (American) Williston Basin have long been described in the geological literature. Gerhard *et al.* (1982) considered that dextral movement along the Colorado-Wyoming and Fromberg zones controlled the geometry of the Williston Basin. They wrote, "There is little question in our minds that sedimentation and structure of the basin are controlled by movement of basement blocks that were structurally defined in pre-Phanerozoic time" (p993). Numerous other authors have documented the location of basement lineaments and associated structures and interpreted their influence on sedimentation. Brown and Brown (1987) recognized major Paleozoic lineament zones based on sedimentation patterns and seismic, aeromagnetic and gravity data. They applied a wrench-style tectonic model to explain sediment thickness and lithofacies variations. Downey *et al.* (1987) used paleolineament zones and Landsat lineaments in the analysis of regional aquifers. Gerhard *et al.* (1987) utilized seismic and other data to determine the structural elements associated with the Nesson Anticline, and interpreted the reactivation history, illustrated as cross-sections, of the vertical faults along the west side of the anticline.

b) Canadian Williston Basin

Early work on the basement tectonics of the prairie provinces commenced in the 1950s. Much of it has since been published in the Williston Basin Symposia volumes. Van Hees (1964) noted features such as depositional boundaries, facies changes, and tectonic boundaries parallel to the Meadow Lake Escarpment. Haites (1959) proposed that the Avonlea structure, southwest of Regina, was a transcurrent fault with a vertical displacement of 300 feet (91 m) and a horizontal displacement of six miles (9.7 km). The Avonlea fault trends northeast and has a right-angle intersection with Avonlea and Moose Jaw creeks. In a later paper, Haites (1960) discussed the mechanics, recognition, location, age, topographic expression, and mineral association of transcurrent faults in Western Canada.

Mollard (1957) has documented "airphoto linears" in Saskatchewan and Manitoba, noting the orthogonal pattern of prominent fracture directions (135° and 046°). Mollard (1987, 1988) later suggested a structural origin for the photo-lineaments and illustrated their connection with known oilfield occurrences. Stauffer and Gendzwill (1987) documented major topographic lineaments and showed that they correlate with Christopher's (1980) sub-Mannville lineaments of southern Saskatchewan. Kent (1987) described the reactivation of Precambrian structural elements and the epeirogenic history of the northern end of the Williston Basin. He detailed the possible paleotectonic controls on sedimentation through the Phanerozoic.

Potter and St. Onge (1991) suggested that the development of structural closures in the Ordovician Red River and Devonian Winnipegosis formations of the Minton pool (south-central Saskatchewan) resulted from reactivation of "conjugate basement structural lineaments".

More recent work by Bezys (1996) along the northeast edge of the Williston Basin in Manitoba concluded that major topographic and photo-lineaments were aligned with Precambrian highs and faults that had been reactivated. Further work by Dietrich and Bezys (1998) and Dietrich and Magnusson (1998) provided more detail on basement-sedimentary cover relationships and basement controls over southwestern Manitoba.

4. Tectonism and Sedimentology: Interpretation Criteria

Movements in the Western Canada Sedimentary Basin have been dominantly vertical throughout Phanerozoic time, but significant horizontal movement has occurred in both large and small wrench-fault systems. "Proving" the existence of a fault in the subsurface is commonly difficult. Reflection seismic data are becoming increasingly reliable, (Dietrich, 1999; Lemieux, 1999), but are commonly ambiguous in delineating subtle subsurface faults. Sedimentological and stratigraphic data must therefore be used to provide supplementary information. The lateral and vertical arrangement of strata and facies in adjacent wells indicates whether a fault separates the two successions. The problem of correctly interpreting homotaxial relationships is not a new one, nor is it academic. Several examples exist in the Williston Basin where a horizontally drilled well "lost" the reservoir as drilling proceeded across small faults with significant offsets. One case study cross-section even depicted the creek marking the vertical fault across which the reservoir was lost – the significance of the creek was apparently overlooked until the post-mortem. Figure 1 shows examples of vertical block movement under compressional and extensional stresses.

Given the same subsurface formation tops or data points, three different homotaxial relationships fit the requisite geometry (Figure 2). The three relationships are: 1) facies change, 2) unconformity-bounded units, and 3) fault contacts. The criteria used in this study to interpret basement-sediment cover interactions associated with Deadwood deposition and erosion are:

1) **Facies Change:** The criteria for making this interpretation include: i) the facies change is reasonable given lithotypes and sedimentary environments; ii) facies arrangement is in accordance with Walther's Law; iii) contacts within the vertical succession are gradational; iv) evidence of transition (interfingering, pinch-outs) must exist; and v) there is minimal evidence of tectonism (fracturing, sulphides). Evidence of tectonism does not preclude a legitimate facies change from one well to another but it does indicate that there may have been on-going fault reactivation which would make a true facies change unlikely.

2) **Unconformable Relationship:** The criteria are: i) the contact between units is sharp, erosive or reworked; ii) the contact meets at least some of Krumbein's (1942) or Shanmugam's (1988) multiple criteria for unconformities; or iii) evidence of transition from one facies to another is not visible in core or on the wireline log trace.

3) **Fault Contact:** The criteria for placing a fault contact between units are: i) lithofacies and wireline log data fail the criteria for a simple facies change or unconformable relationship; ii) tectonic deformation is evident in the core or outcrop, i.e. fracturing, sulphide deposition, hydrothermal alteration; iii) surficial topographic or photo-

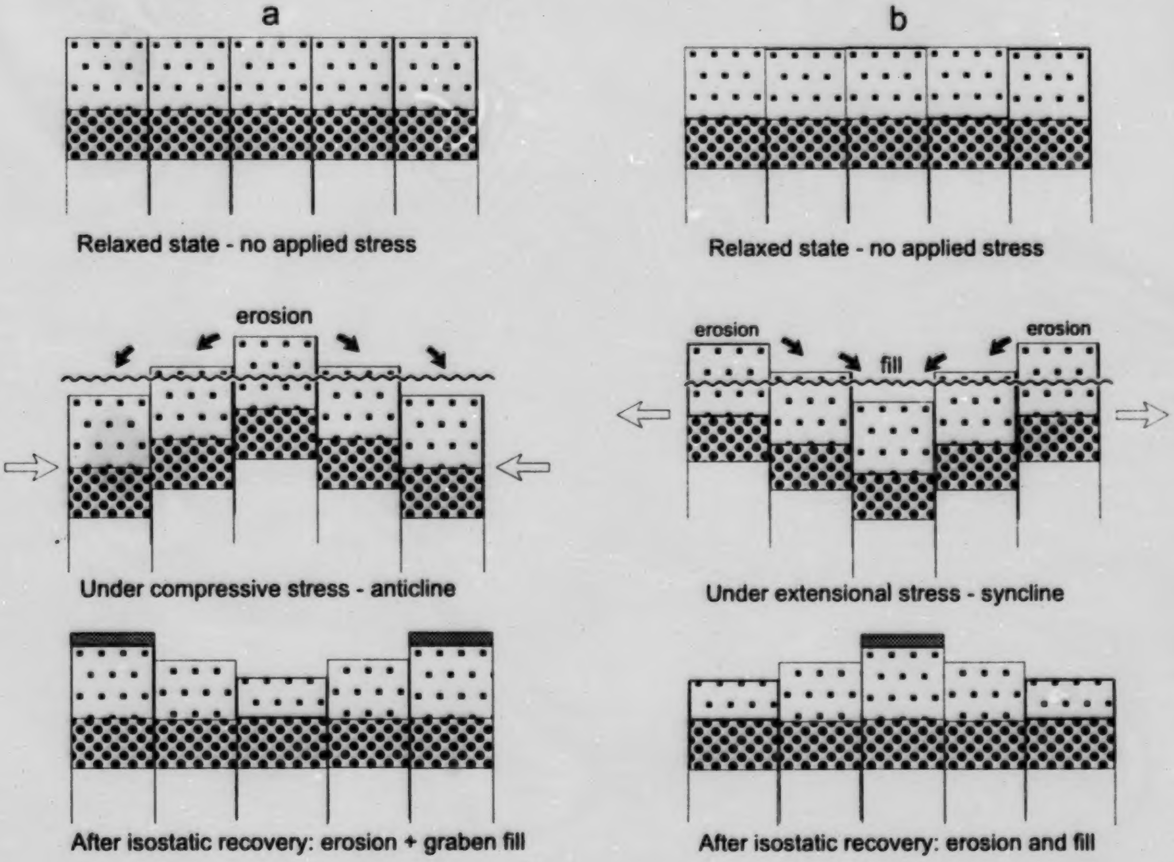
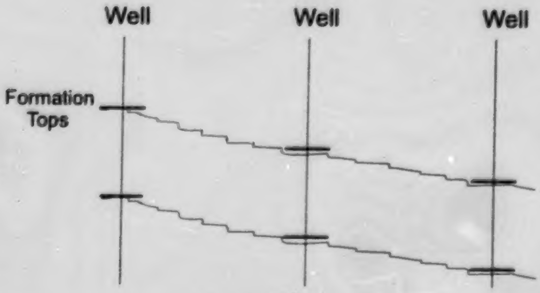

a
b
Relaxed state - no applied stress
Relaxed state - no applied stress
erosion
erosion
erosion
fill
Under compressive stress - anticline
Under extensional stress - syncline
After isostatic recovery: erosion + graben fill
After isostatic recovery: erosion and fill

Figure 1 - Differential erosion of flexing blocks a) under compression and b) under extension.

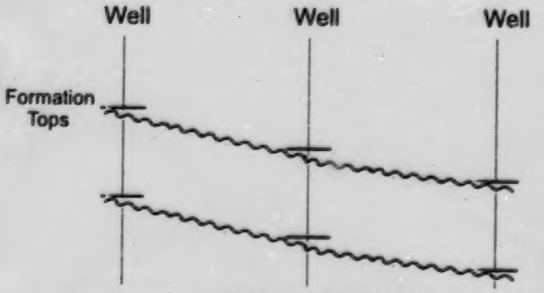
lineaments are present between the wells; iv) a fault is indicated by gravity, aeromagnetic or seismic data; or v) there is substantial dislocation of major unconformities throughout the vertical section.

5. Tectonism: Timing and Effects

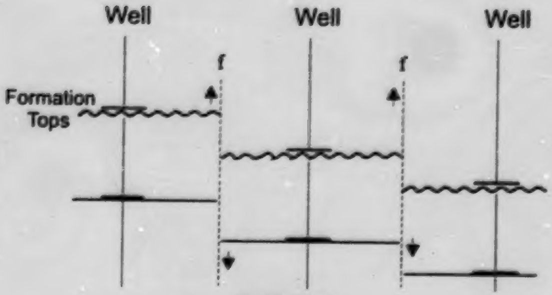
This classification is set up in a similar manner to that of homotaxial relationships: the categories are presented in their simplest form, essentially as three end-members of what would amount to a ternary plot.



1. Facies Change



2. Unconformity



3. Fault + Unconformity

Figure 2 - Three different homotaxial relationships based on the same subsurface formation tops.

There are two very different "preserved" effects of tectonism to assess: the actual deformation of the rock, and the alteration in the regional facies or lithofacies pattern and thickness.

a) Tectonism Occurring During Deposition

1) Development of morphotectonic features (e.g. alluvial fans).
2) Facies will be aligned or oriented consistent with fault trends (e.g. river channels, glacial scours, reef trends).
3) Development of *depositionally* thickened or thinned sections.

b) Tectonism Occurring Post-deposition, but Pre-lithification

1) Deformation of unlithified layers (i.e. contorted, disrupted bedding).
2) Development of seismites and dewatering structures.
3) Seismically triggered turbidite flows or other forms of mass-wasting, mass movement.

c) Tectonism Occurring Post-lithification

1) In rock: fracturing, stylolites (pressure solution), solution enhancement, sulphide deposition, pyrobitumen, other types of hydrothermal alteration.
2) Differential beveling of unconformities.
3) Development of *preservationally* thickened or thinned sections.
4) Structural drape of more ductile layers, such as anhydrite or shale.

Tectonism can also be ranked according to the frequency and severity of the seismic event.

i) Catastrophic and episodic:
Catastrophic in the context of a rare event, with the release of large amounts of energy. If tectonism is catastrophic, we would expect to see: sudden shifts in base level and water depths, effecting a violation of Walther's Law through sudden changes in the environment of deposition; scours due to tsunamis; lag deposits resulting from debris and ripped-up clasts settling out of the water column; seismites; fracture of lithified rocks; episodic pulses of hydrothermal fluids; marked differential erosional beveling; and/or reversals of fault movement.

ii) Cyclic with regular frequency and low to moderate amounts of energy released:
A cyclic pattern of tectonism with moderate to low releases of energy, possibly due to cratonic flexuring (causing epeiric sea-level changes) would result in: cycles observable in the preserved sediments–facies perturbations; small-scale debris flows and moderate development of seismites; some erosional beveling of lithified sections; and probably little indication of

tsunamis, instead would see low-level seiche conditions.

iii) Continual (in the geological-time sense), with low to very low amounts of energy released:
If tectonism is continual and very subtle, possibly due to slow isostatic recovery after large plate movements or cratonic flexuring, the effects will likely show more in the regional pattern of sedimentation and preservation: thickened depositional sections (but not debris); tectonic control of geomorphologic features, i.e. reefs locating on horsts or ridges, sand bars accreting along trends of slight positive relief, river channels locating within graben trends, lake sediments similarly occurring within graben boundaries; subtle erosional beveling; may not see much brittle fracture (strain being released continuously, rather than catastrophically) or hydrothermal alteration in lithified sediments; should not see instantaneous "facies changes"; and may not see Pratt's (1998) syneresis cracks if the energy release is not adequate to trigger sudden dewatering.

6. Results and Discussion

The results of core examination clearly indicate that the Deadwood sandstones have undergone several episodes of tectonism, the first of which possibly occurred syn-depositionally. The presence of zircons and strained quartz indicates that Precambrian granite monadnocks were exposed and weathering during deposition, perhaps as a result of cratonic stresses. Paleorelief on the Precambrian surface may have been considerable.

Core control is insufficient to postulate shifting facies belts or syn-depositional tectonics with confidence. Small-scale, 1 to 1.5 m thick, fining-upward cycles in Deadwood sandstones are, however, genetically linked to eustatic sea-level changes coupled with accelerated basin subsidence, both of which may have occurred gradually (i.e. non-catastrophically) in response to global tectonic events.

Post-depositional activity is suggested by certain sedimentary structures. Several cores (e.g. 02/05-07-14-10W3) show slumping and chaotic bedding, interpreted as seismites. Flat-pebble conglomerates are also present in several cores (e.g. 04-28-38-24W3 and 01-25-54-26W3). Historically, this lithofacies, which is dominantly and distinctly Cambrian, has been interpreted as tempestites (Sepkoski, 1982). These "storm" deposits may have been the result of tsunami activity. They are a global phenomenon, not limited to the Williston Basin or the Western Canada Sedimentary Basin.

Global tectonic events and sea-level changes of Cambrian age have been discussed by Mound and Mitrovica (1998), who proposed that true polar wander may be responsible for second-order sea-level variations. Kirschvink *et al.* (1997) have calculated anomalously fast rates of rotation and latitudinal shift during the Vendian-Cambrian transition to the end of the Middle Cambrian, suggesting this resulted from inertial interchange true polar wander. If this were the case, it provides a possible explanation for the high frequency of seismite structures in Cambrian sedimentary rocks (in contrast to Devonian strata, for instance). Isostatic adjustments resulting from continental movement may have continued to "ripple" through continental masses for some time, affecting sedimentation – in particular the generation of seismites – and sediment preservation.

Post-lithification events in the Deadwood Formation are exemplified by the shearing of shales and sandstones, fracturing and vein fill, and anomalously rubbly core recoveries (06-13-02-19W2 and 04-10-33-01W3). Alberta cores show greater concentrations of sulphide mineralization, but concentrations of pyrite can be seen in these two wells. Post-lithification events are also indicated by anomalously thick or thin sections of Deadwood. Some uplifted blocks were preferentially eroded prior to Winnipeg deposition, probably in a manner similar to that diagrammatically shown in Figure 1. Other downdropped blocks received additional sediments through essentially a graben-fill process. Little evidence of debris-fill or turbidites is present in the cores, which suggests that thickness variations are due to either post-lithification erosion or very gradual graben subsidence. Compaction and late dewatering are not considered significant factors in creating these thickness differences as there are no shale beds of significant thickness.

7. Economic Considerations

The Deadwood Formation of Saskatchewan has potential as an oil and gas target. Porosities and permeabilities of the sandstone units are generally moderate to good. The lack of a confirmed Cambrian source rock does not preclude the Deadwood as a target. Fault reactivation and block uplift through geological time facilitate the migration of younger fluids into older reservoirs. Integrated mapping would highlight these target blocks and would also clarify preferred paths for horizontal drilling.

Deadwood hydrocarbon traps will be primarily structural. Surficial features often give clues as to the underlying structure (the present is truly the key to the past). The North Saskatchewan and other rivers show the straight courses and right-angle bends of a classic orthogonal system. The presence of an orthogonal system has been affirmed in Alberta with seismic and aeromagnetic data. In other areas of Saskatchewan, evidence such as anticlinal structures suggests that small-scale wrench-fault systems have been active. Eyehill Creek is an example. Near Senlac (Tp 40, Rge 25, 26W3), a strong surficial orthogonal grain creates small discrete blocks. Detailed subsurface mapping and construction of structural cross-sections are required to confirm these possibilities, and to determine sealing configurations and orientations.

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An Examination of the Hydrocarbon-generating Potential of the Deadwood Formation and Black Island Member, Winnipeg Formation, Saskatchewan

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Seibel, C. and Bend, S. (2000): An examination of the hydrocarbon-generating potential of the Deadwood Formation and Black Island Member, Winnipeg Formation, Saskatchewan; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

1. Introduction

The Williston Basin area is a significant petroleum province that contains pooled hydrocarbons exhibiting a range of characteristics through which their familial relationships have been defined (Williams, 1974; Dow, 1974; Zumberge, 1983; Brooks *et al.*, 1987; Osadetz *et al.*, 1992, 1994; Osadetz and Snowdon, 1995; Obermajer *et al.*, 1998). Despite on-going exploration activity since 1953, few exploration wells have met with economic success or have even intercepted hydrocarbons (i.e. light oils) within the Deadwood and Winnipeg formations. Little is therefore known about the characteristics and source (or sources) of oils in these rocks, or of the petroleum system to which they may belong (Bend *et al.*, unpubl. data).

In 1978, the Shell Oil 23X-9 Larson (Newporte field, Renville County, North Dakota) yielded 37 m³ of oil during a drillstem test. Eagle Operating re-completed the well in 1996 and produced 9540 m³ during the first six months of production from a basal sandstone in the Deadwood Formation (Hendricks *et al.*, 1998). Later Newporte wells also produced significant amounts of oil from the same sandstone. More recently, the Berkley et al. Midale 8-16-6-11W2 well in southeastern Saskatchewan initially tested at 1050 b/d of clean 55° gravity oil at 1150 psi tubing pressure from the Ordovician Winnipeg sand (Oil and Gas Journal, February 8, 1999). Wells which produce from the Winnipeg sand (Black Island Member) include the Berkley et al. Midale 8-16-6-11W2 (>15 000 m³ cum. prod.), Berkley et al. Midale 16A-20-6-11W2 (>1700 m³ cum. prod.), and Berkley et al. Hartaven 7-2-10-9W2 (>28 000 m³ cum. prod.) (Kreis, pers. comm., 2000). This production hints at the existence of another significant petroleum system within the Williston Basin area.

The stratigraphy of the Deadwood in southern Saskatchewan is poorly understood. Fossil evidence in the lower portion of the Deadwood is meagre, and markers like the 'Pika', which assist in well-to-well correlations in parts of Alberta, appear to be generally absent east of the Swift Current Platform. These factors make correlation between lower Deadwood strata in Saskatchewan and Middle and Upper Cambrian rocks in western Alberta difficult (Slind *et al.*, 1994; Hein and Nowlan, 1998; Greggs and Hein, this volume). In the southern Williston Basin area, the Deadwood is dated as Late Cambrian to Early Ordovician (Lochman-Balk and Wilson, 1967).

2. Objectives and Goals

This summary outlines the progress of a study that seeks to identify the hydrocarbon source of the Deadwood and Winnipeg oils and condensates within the Williston Basin area and to identify their petroleum system.

3. Methodology

The initial phase of this work focuses on the spatial and temporal distribution of facies and the potential source rocks. Cross-sections were constructed that trend northerly, northwesterly, and easterly (Figure 1). Thus section A-A' originates at the EM Larson 9-11 "R" well (Newporte field, North Dakota) and the other sections are linked to it. The Deadwood and Winnipeg cores from wells on cross-sections A-A' and B-B' (Figures 1, 2, and 3) have been logged, correlated, and analyzed by light microscopy augmented by LECO total organic carbon analysis, RockEval pyrolysis, and gas chromatography-mass spectroscopy (gc-ms).

4. Lithological Characteristics

a) Deadwood Formation

A generalized lithologic description of the Deadwood has been derived from core from the EM Larson 9-11 "R" (Figure 4) and Founders et al. Hartaven 12-1-10-9W2 wells.

The basal sandstone unit of the Deadwood Formation grades from a poorly sorted, fine- to very coarse-grained immature sandstone upward into a well sorted, well rounded, coarse-grained quartzose sandstone (Figure 4a). It is overlain by a bioturbated, glauconitic unit composed of siltstones and sandstones with traces of carbonate and thin, dark grey shale (Figure 4b) generally devoid of organic matter (Figure 4b-i). The

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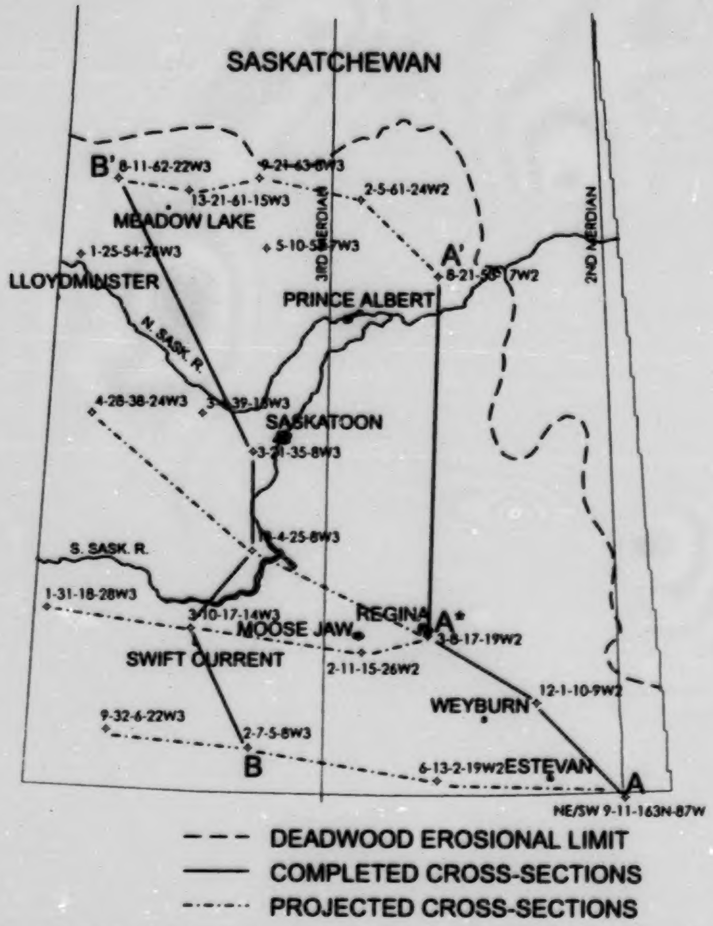

Figure 1 - Map of the current study area showing cross-section locations. Cored intervals of Winnipeg and/or Deadwood strata are available in all wells selected.

uppermost unit is a fissile, waxy, dark grey-green shale with a trace of pyrite (Figure 4c).

b) Winnipeg Formation

The Winnipeg Formation is typically divided into the Black Island (O) and Icebox (Y) members. Along transect A-A', the thickest section of the Black Island Member is present in the 12-1-10-9W2 well where it comprises six units (in ascending stratigraphic order): Unit 1–silty bioturbated sandstone; Unit 2–bioturbated, pyritic silty shale; Unit 3–sandstone with pyrite (as blebs or inter-granular) and poor porosity; Unit 4–sandstone with good porosity; Unit 5–silty bioturbated shale; and Unit 6–bioturbated sandstone.

The sequence in the University of Regina 3-8-17-19W2 well is similar to that in 12-1-10-9W2 with the exception that Unit 6 is absent (Figure 2).

At the EM Larson 9-11 "R" well in the Newporte field, the Black Island Member is composed of a basal 8 m thick, dark grey shale (Hendricks *et al.*, 1998) that has fine laminae of amorphous organic matter and alginite (Figures 4d, 4d-i, and 4d-ii), and an overlying bioturbated sandstone. Preliminary interpretation suggests that the basal shale, which has not been reported by other workers (e.g. Lochman-Balk and Wilson, 1967; Vigrass, 1971; Carlson and Thompson, 1987; Ellingson and LeFever, 1995), becomes increasingly silty and bioturbated northward and may be correlative with Unit 5 in the 12-1-10-9W2 and 3-8-17-19W2 wells (Figure 2). The overlying sandstone is correlative with Unit 6 in 12-1-10-9W2 (Figure 2).

The Icebox Member comprises bioturbated, brown silty shale and a finely laminated, brown to dark grey pyritic shale.

5. Influence of Precambrian Relief

The thickness of the Deadwood changes along cross-sections A-A' and B-B' (Figures 1, 2, and 3). Beds are, however, locally correlatable. The Deadwood thins towards its northern and eastern erosional limits, and the colour of the shale, siltstone and sandstone units changes to purple and red, possibly a weathering feature. Along cross-section B-B', lower strata are not amenable to correlation, possibly because of complex facies changes that occurred as topographic lows on the Precambrian basement were infilled. For example, at Hartaven and around Swift Current, the basal sandstone unit present at EM Larson 9-11 "R" is absent. Higher in the Deadwood succession, lithological units appear to be increasingly correlatable, probably because more uniform depositional conditions prevailed toward the end of Deadwood deposition.

Along the eastern margin of the basin, Deadwood and Winnipeg strata were deposited onto and around Precambrian monadnocks, which thus appear to have exercised a degree of control on the lithofacies (Kreis, pers. comm., 1999, 2000a, and 2000b) and, perhaps, on the organofacies. Anomalous lithologies, such as the Winnipeg basal shale at EM Larson 9-11 "R", may reflect sites of restricted circulation.

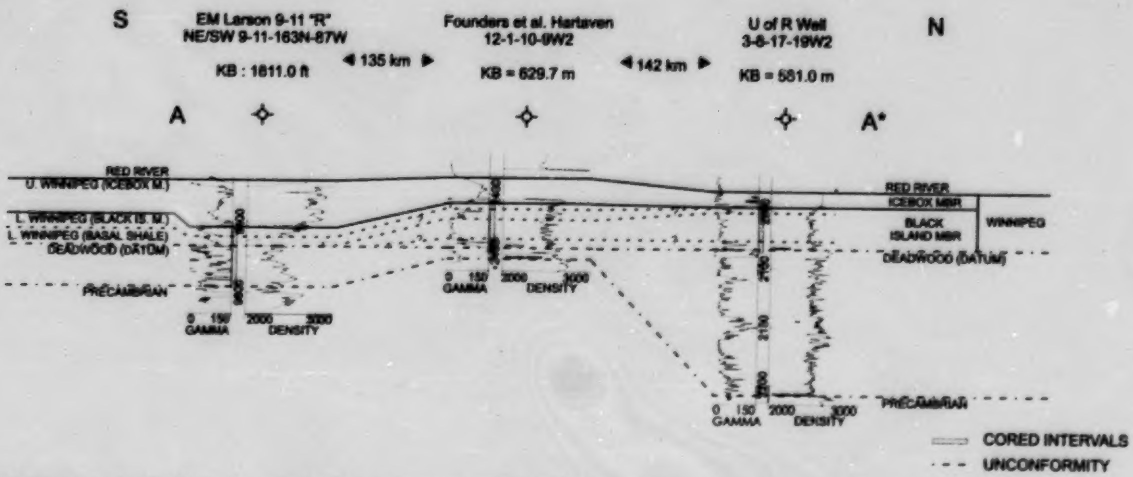

Figure 2 - Stratigraphic cross-section A-A (southern portion of A-A'; Figure 1) showing gamma-ray and density log traces and location of cored intervals. The datum is the top of the Deadwood Formation. Wherever KB is given in feet, the corresponding depths are in feet. Winnipeg and Deadwood core in the Kelsey Lake 8-21-53-17W2 well at the northern end of A-A' has also been logged and analyzed.*

6. Geochemical Characteristics

a) Source Potential

Throughout the Deadwood Formation, core samples along sections A-A' and B-B', contain only sporadic algal material (Figure 4b-i). Petrology and TOC/RockEval data from examined samples indicate that the Deadwood Formation is non-prospective (Figure 4). TOC values along section A-A' attain a maximum of 0.8 wt% (EM Larson 9-11 "R": 2894.1 m [9495 ft]) with a typical range of 0.2 to 0.4 wt%. RockEval S2 values are generally below 1.0 mg/g.

The only facies with prospect as a potential source is the basal shale of the Winnipeg Formation at EM Larson 9-11 "R". In hand specimen, networks of bitumen and visible oil staining were identified in bedding of the shale. This shale yields TOC values ranging from 1.5 to 1.8 wt% with corresponding S2 values ranging from 7 mg/g to 10 mg/g; TOC values diminish markedly to less than 0.5 wt% at 3-8-17-19W2 along section A-A'. Petrographic analysis of the basal Winnipeg shale shows the predominance of a Type I/II kerogen composed of *Leiospheridia*, filamentous alginite, and amorphous kerogen (Figures 4d-i and 4d-ii). The kerogen is generally concentrated in laminae surrounded by a weakly autofluorescing amorphous background; laminae range in thickness from tens of micrometres to several millimetres. Bitumen networks and oil staining were also seen in the Black Island Member sandstone of the EM Larson 9-11 "R" and Hartaven cores.

b) Oil/Oil and Oil/Source Relationships

A sample of oil-stained Cambrian basal sandstone from the EM Larson 9-11 "R" well was extracted and analyzed by gc-ms. The extract has a biomarker signature identical to that of the Newporte-produced oils. The Deadwood Formation oil and extract are associated with an „alkane distribution up to C_{35}, a low pristane to phytane ratio (0.45), a m/z 191 ion chromatogram dominated by the C_{30} $\alpha\beta$ hopane, a low Ts/Tm ratio, and very low tricyclic and tetracyclic compounds and no C_{21} diasteranes (Figure 5a).

An organic-rich sample of the Winnipeg basal shale from the EM Larson 9-11 "R" was extracted and analyzed by gc-ms (Figure 5b). The extract is associated with a higher proportion of tricyclic compounds and diasteranes (rearranged steranes) compared to Deadwood and Winnipeg oils. Both the Deadwood oil and the basal shale extract have a similar proportion of C_{28} steranes, which is also higher than that of the Red River oils. In contrast, the Winnipeg basal shale features the lowest proportion of C_{29} steranes. Thus the Winnipeg basal shale does not appear to be the source for Deadwood or Winnipeg hydrocarbons due to a low associated TOC, low extract yield and apparent dissimilarity in biomarker signature.

Northward along transect A-A' or B-B' from southeastern Saskatchewan (Figures 1, 2, and 3), the relative amount of organic matter, as kerogen, diminishes markedly in Deadwood and lower Winnipeg strata. Similarly, towards the Swift Current Platform the source potential of the Deadwood diminishes. These results were anticipated, since our transects trend toward the Swift Current Platform or the northern erosional edge (i.e. sub-crop) of the Deadwood and Winnipeg and away from a possible depocentre of the basin in North Dakota (a few wells in North Dakota penetrate much thicker sequences of Deadwood and lower Winnipeg Formations than those of southern Saskatchewan, but generally lack core).

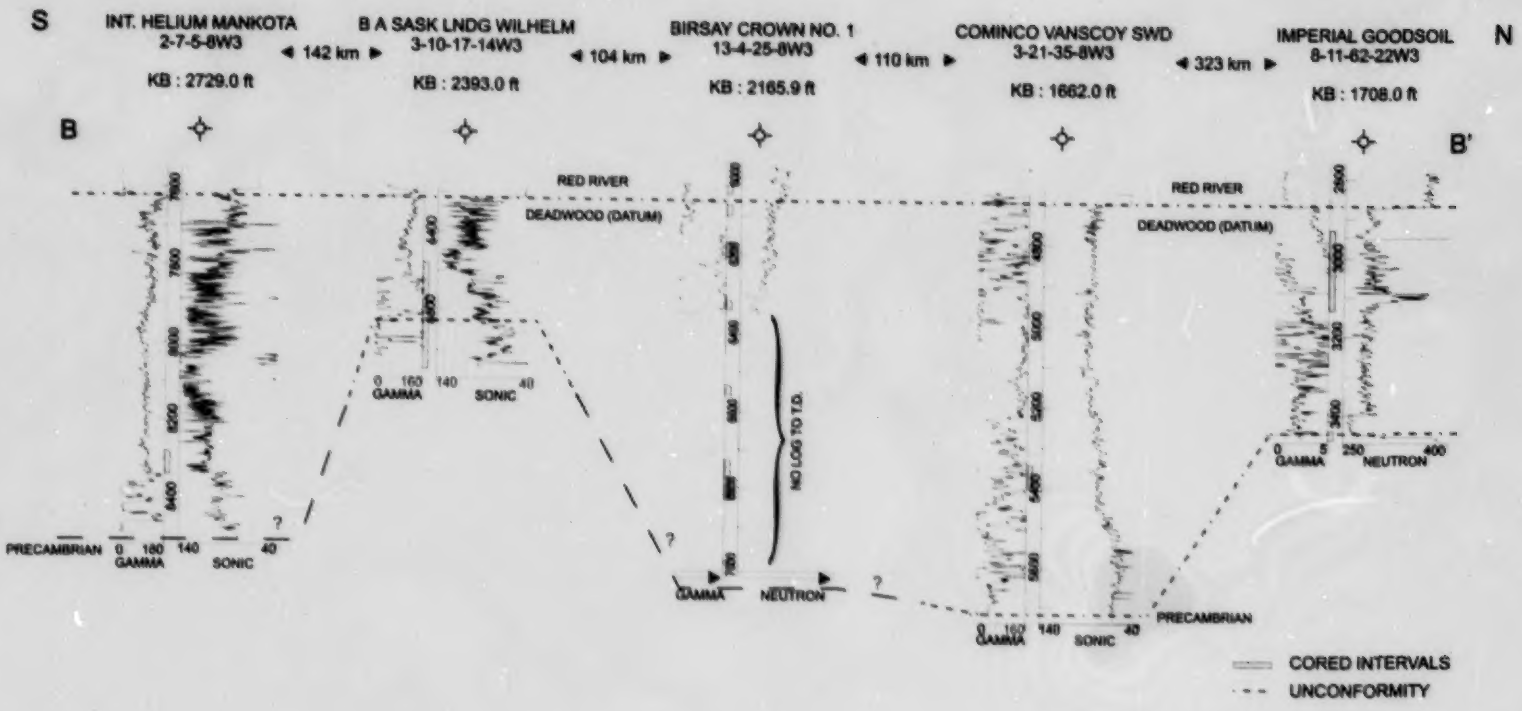

Figure 3 - Stratigraphic cross-section B-B' (location shown in Figure 1) showing gamma-ray and density or neutron log traces and location of cored intervals. The datum is the top of the Deadwood Formation. KB and depths are in feet. Note that the Deadwood Formation is unconformably overlain by the Yeoman Formation.

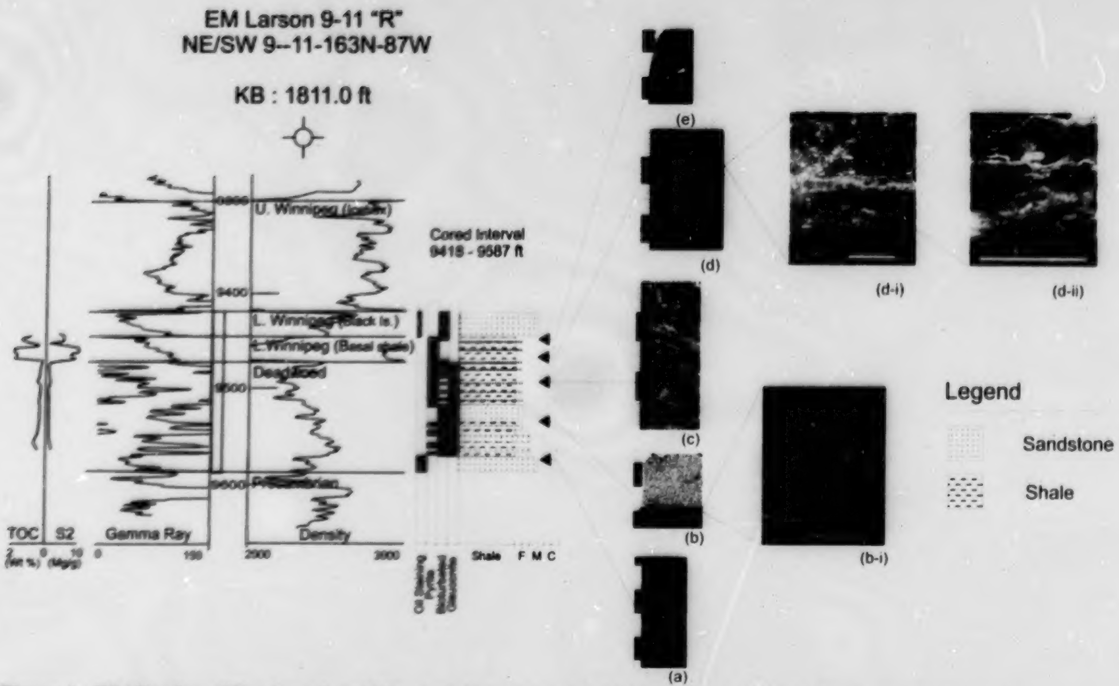

Figure 4 - Wireline log of Deadwood and Winnipeg formations from EM Larson 9-11 "R" showing cored interval, a generalized lithology, TOC and RockEval (S2) data and photographs of selected slabbed core and, where appropriate, corresponding autofluorescent micrographs depicting the character and distribution of kerogen (L = Leiospheridia). The photographs of slabbed core were taken in white light; the scale bar in each photograph is in centimetres. Each micrograph includes a 50 µm scale bar (in white). The sample intervals of the photographs are: (a) 2972.1 m (9571 ft), (b) 2912.7 m (9556 ft), (c) 2893.8 m (9494 ft), (d) 2885.8 m (9468 ft), and (e) 2881.9 m (9455 ft).

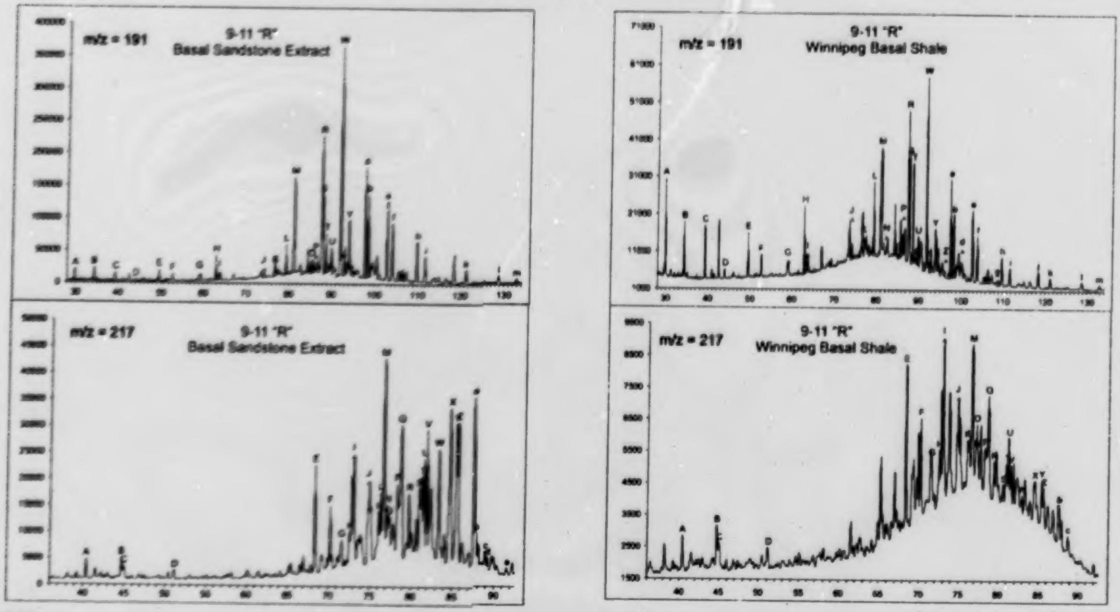

Figure 5 - M/z 191 and 217 mass fragmentograms for the Deadwood basal sandstone (a) and Winnipeg basal shale (b) extracts; samples from EM Larson 9-11 "R".

The oil produced from Lower Paleozoic strata in the Newporte field may not be locally sourced as it shares a biomarker similarity with oil produced from the Winnipeg Formation in Saskatchewan (Bend *et al.*, unpubl.). This suggests that a more regional source (or sources) is (or are) present within the Williston Basin.

7. Conclusions

The shales of the Deadwood Formation throughout southern Saskatchewan have a low hydrocarbon source potential which diminishes towards its northern erosional edge and the Swift Current Platform. The most prospective lithology, the Winnipeg basal shale at EM Larson 9-11 "R", appears to be an unlikely source of the Deadwood (and Winnipeg) oil, based on TOC content, extract yield and biomarker signatures. The oils of the Newporte field are similar in biomarker composition to Winnipeg oils of southern Saskatchewan, but are distinct from the oils of the Red River Formation.

8. Acknowledgments

We thank Hendricks and Associates for permitting sampling of the EM Larson 9-11 "R" core, and the Subsurface Geological Laboratory (SEM) for core access and samples, the Energy Research Unit for petrographic facilities, and DGSI Labs, Texas, for the geochemical analyses. We also thank Jim Christopher, Fran Haidl, and Kim Kreis for their constructive reviews of this summary. This project was initiated by funds provided via a NSERC research grant (SLB) and support from Vista Energy Inc.

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Basement Controls on Red River Sedimentation and Hydrocarbon Production in Southeastern Saskatchewan

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Kreis, L.K. and Kent, D.M. (2000): Basement controls on Red River sedimentation and hydrocarbon production in southeastern Saskatchewan; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

1. Introduction

Discovery of significant oil reserves in Red River strata in the Berkley et al. Midale 4-2-7-11W2 well in December 1995, together with Saskatchewan government incentives such as reversion of deep rights to the Crown in 1998 and reduced royalties for deep exploration and development wells, set the stage for recent hydrocarbon exploration activity targeting Red River rocks and, to a lesser extent, the Winnipeg Formation. Between December 1995 and December 1999, over 280 wells have been licensed to explore the Red River in southeastern Saskatchewan. More than half of these were licensed to drill to the Precambrian; they have provided valuable new information about the Precambrian basement surface, basement structure and lithology, and relationship between basement and overlying strata. Oil exploration companies have taken cores in most of these wells, greatly contributing to our understanding of deep formations.

Prior to the Midale discovery, Red River production was restricted to 16 wells widely distributed in the Minton, Hummingbird, Lake Alma, Beaubier, Oungre, Bromhead, and Weir Hill areas near the American border in southeastern Saskatchewan (Figure 1). Since then, producing reservoirs have been discovered up to 75 km northward into the Chapleau Lake area. Numerous seismic surveys covering large areas to the north and west of these producing areas have been run in recent years, holding the promise of further drilling and more discoveries. Recently, a deep well test has been licensed to drill to the Precambrian basement in Township 27 and Range 18 west of the second meridian, some 125 km north of Chapleau Lake. In the 38 years following the first discovery in 1957 until the Midale discovery, oil production from Red River reservoirs totaled just over 226 000 m^3 from 16 wells. In fewer than four years between the Midale discovery and mid-September 1999, more than one million cubic metres of oil have been produced from 115 new wells.

This paper focuses on stratigraphic evidence for basement controls on Red River sedimentation and hydrocarbon production in southeastern Saskatchewan, an area on the northeastern margin of the Williston Basin (Figures 1 and 2). It also discusses spatial relationships and orientations of basement features and lineaments.

2. Regional Basement Features

The origin and nature of the Williston Basin are unclear and their discussion is beyond the scope of this paper (for further information see Stewart, 1972; Dickinson, 1976; Gerhard *et al.*, 1982; Kent, 1987; Crowley *et al.*, 1985; Fowler and Nisbet, 1985; Green *et al.*, 1985a, 1985b; Green *et al.*, 1986; Quinlan, 1987; Gerhard *et al.*, 1991; Sims *et al.*, 1991; Burwash *et al.*, 1993; Nelson *et al.*, 1993; Kent and Christopher, 1994; Baird *et al.*, 1995; and Gibson, 1995).

Three major basement provinces are recognized from regional magnetic data in the Williston Basin area (Green *et al.*, 1985a, 1985b; Baird *et al.*, 1995; Gibson, 1995; and Kreis *et al.*, 2000). Archean (>2.5 billion years) rocks of the Wyoming Province in the west and the Superior Province in the east are separated by an intervening collage of Proterozoic rocks belonging to the Trans-Hudson Orogen (1.8 to 1.9 billion years) (Figure 2). The Trans-Hudson Orogen is considered by Lewry and Collerson (1990) to be a major component of the Early Proterozoic Pan-American orogenic system, extending from South Dakota, across Hudson Bay, Greenland, and Labrador. Results from the COCORP deep reflection seismic transect in northeastern Montana and northern North Dakota suggest that the Trans-Hudson Orogen is probably cored by an Archean crustal fragment that was caught up in the collision of the two Archean paleocontinents (Baird *et al.*, 1995).

Mappable features that are spatially related to the boundaries of the basement provinces (Figure 2) and that are defined by thickness anomalies in various Phanerozoic formations or by geophysical mapping include the Birdtail-Waskada axis, a well known north-south lineament lying immediately east of the Saskatchewan-Manitoba border. Characterized by numerous structural and stratigraphic irregularities (McCabe, 1967; Dietrich and Magnusson, 1998), it directly overlies the boundary between the Trans-Hudson (Churchill) and Superior provinces. Andrichuk (1959), Kent (1960), Christopher (1961), Kendall (1976), and Kreis (1991) document thinning of various Phanerozoic units in a north-south zone parallel to the Saskatchewan-Manitoba border in southeastern Saskatchewan. This area coincides with the Nelson

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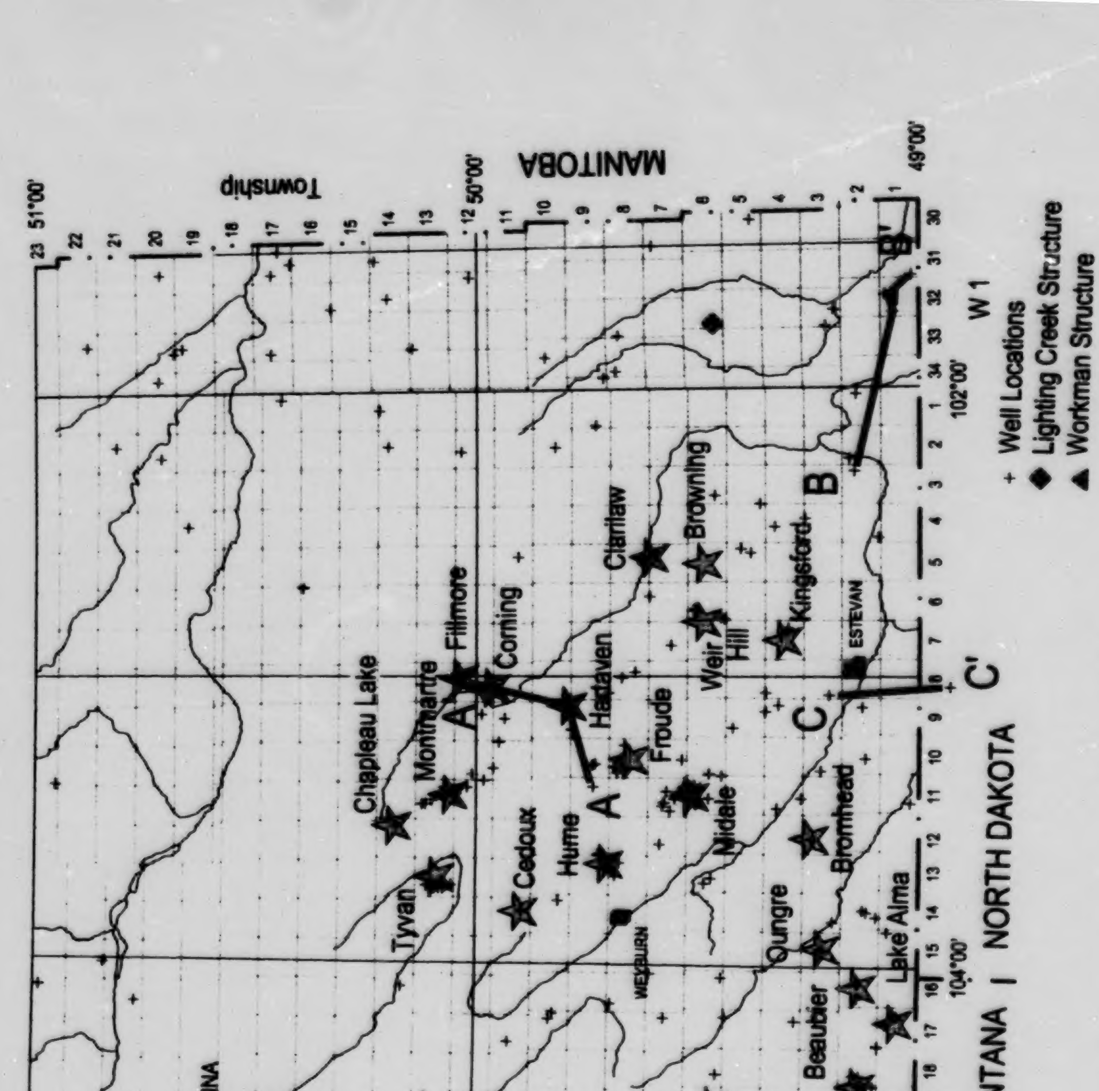

Figure 1 - Study area showing areas of Red River hydrocarbon production in southeastern Saskatchewan and cross-section locations discussed.

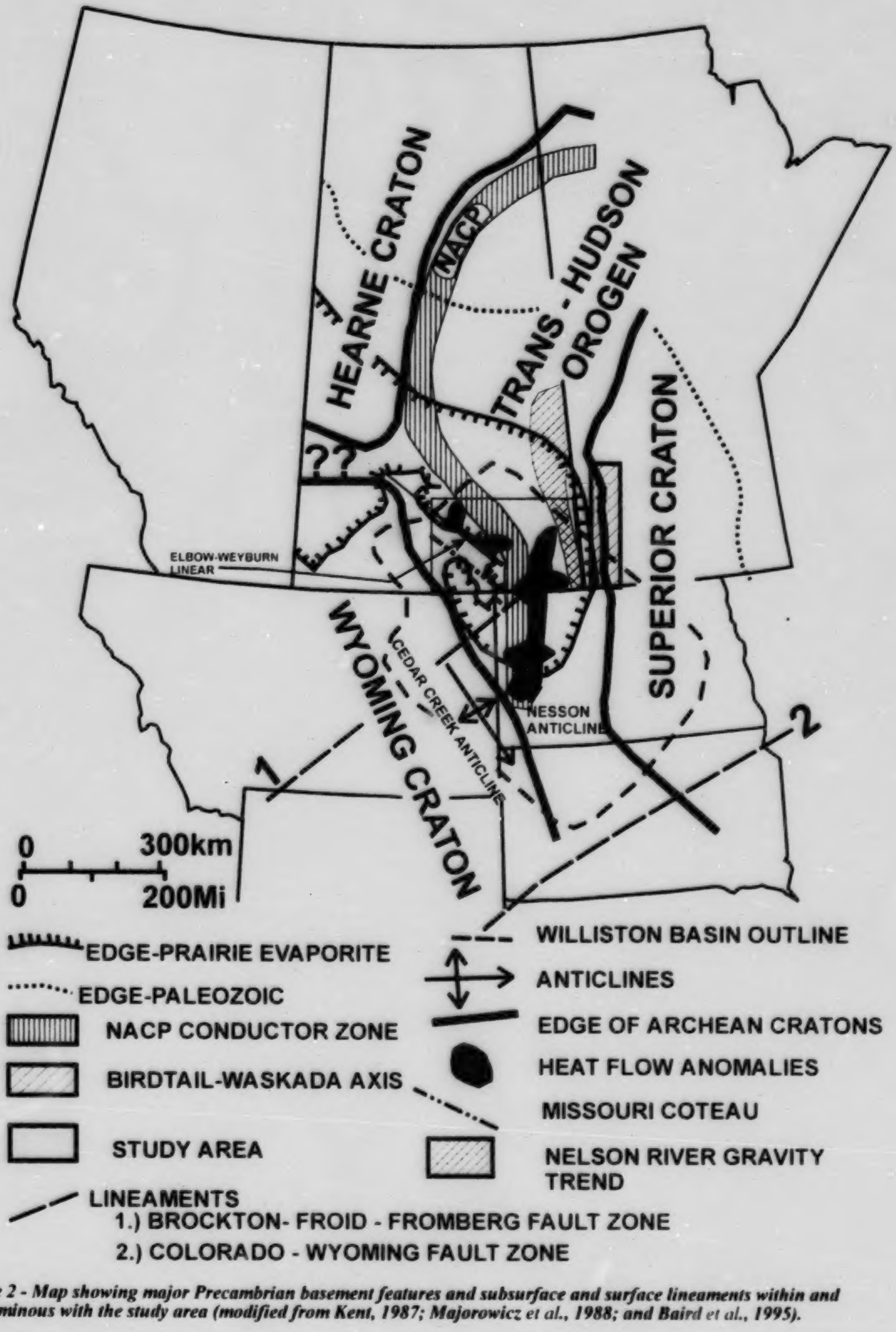

Figure 2 - Map showing major Precambrian basement features and subsurface and surface lineaments within and conterminous with the study area (modified from Kent, 1987; Majorowicz et al.*, 1988; and Baird* et al.*, 1995).*

River Gravity Trend (Macdonald and Broughton, 1980) (Figure 2).

Two wells, Imperial Lightning Creek 16-7-6-32W1 and Cherokee et al. Workman 2-34-1-32W1, in southeastern Saskatchewan are located in a north-south zone parallel to the nearby Birdtail-Waskada axis. They show evidence of faulting which could be attributed to basement movements within this major paleotectonic zone (Figures 1 and 2). The evidence includes Kendall's (1976) observation that the Red River interval is anomalously thick (more than 60 m greater than normal) in the Lightning Creek well. He attributes this thickening to apparent repeated sections in geophysical well logs as well as repetition of Deadwood lithologies in well cuttings at a stratigraphic level where Red River rocks would normally occur. He also comments on the unusual thickness of dolomitized rock in this well. This feature contrasts with the partially dolomitized Yeoman sections in nearby wells and indicates an unusual diagenetic history, possibly related to faulting. The Workman well is cored in the Bighorn Group (see Figure 3 for stratigraphic nomenclature) over the interval from 2315 to 2327.7 m which includes the lower Coronach, Lake Alma Anhydrite and "C" Laminated. The upper 7.1 m of the core have a typical Herald succession of burrow-mottled limestone overlying a thin laminated dolostone all belonging to the Coronach. They rest upon a 3 m thick evaporitic interval consisting of 1.6 m and 0.8 m of interlaminated dolostone and anhydrite separated by 0.6 m of laminated dolomicrite and oolitic-intraclastic dolo-wackestone. The evaporitic interval is in contact with typical "C" Laminated rocks. A repeated sequence of Lake Alma Anhydrite forms the next 5.6 m of core. In addition, the interval from 2325 to 2325.7 m contains deformed dolomicrite with a dip of 40° to 45°. Repetition of strata in both the Lightning Creek and Workman wells suggests reverse or thrust faulting may have occurred in these intervals. The Interaction Renata Workman 3-27-1-32W1 well shows a pronounced thinning of Red River strata over a basement high (Figure 4). The anomalous thinning and the faulting in this well suggest syn- and post-depositional reactivation of the basement.

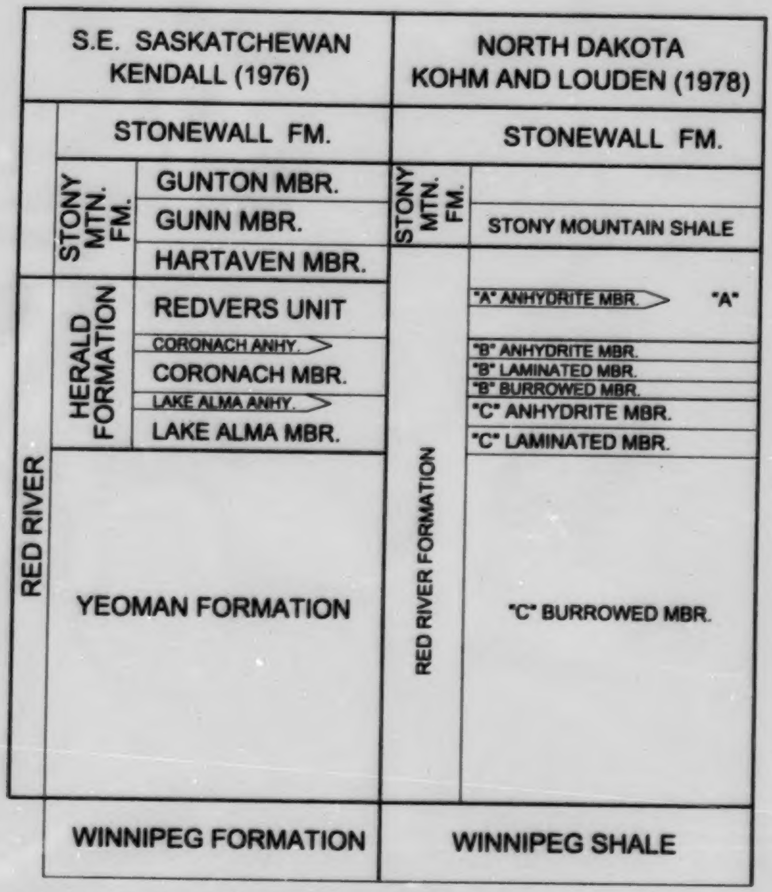

Figure 3 - Correlation chart showing stratigraphic nomenclature of Red River (Yeoman and Herald) and adjacent strata in Saskatchewan and North Dakota.

The coincidence of the North American Central Plains electrical conductivity anomaly (NACP) with the Trans-Hudson Orogen implies a Precambrian basement structural control to the feature (Figure 2). The presence of high-grade metamorphic rocks in drill core samples and of a narrower width of the Trans-Hudson segment in North and South Dakota relative to the exposed segment in the Canadian Shield suggest that compression during collision was greater in the Williston Basin area (Baird *et al.*, 1995). Majorowicz *et al.* (1986, 1988) and Osadetz *et al.* (1998) discuss a heat flow anomaly that is situated near Estevan, immediately east of the NACP along 103°W (Figure 2). It juxtaposes an electrical conductivity anomaly found from a magnetotelluric (MT) study reported by Jones and Savage (1986). Both the heat flow and electrical MT conductivity anomalies coincide with a significant Williston Basin feature, the Nesson Anticline (Majorowicz *et al.*, 1988), which has been active throughout Phanerozoic history (Gerhard *et al.*, 1982).

Features that appear to be spatially related to the interpreted northeastern margin of the Wyoming Province in southeastern Saskatchewan include some predominantly

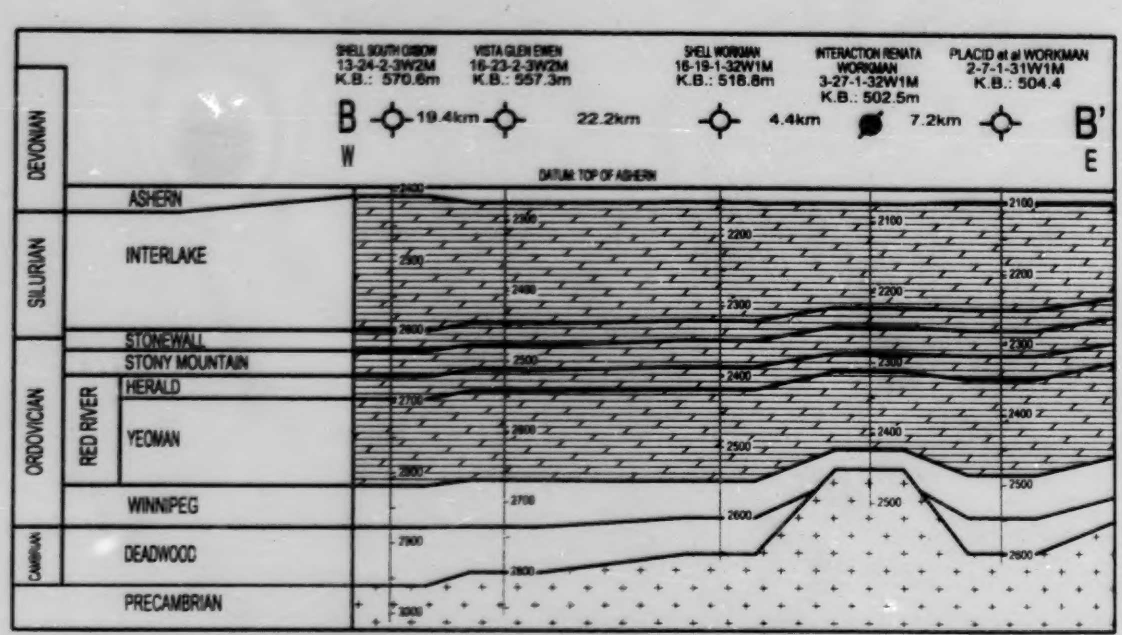

Figure 4 - Cross-section B-B' (see Figure 1) showing Precambrian paleotopographic high in the Interaction Renata Workman 3-27-1-32W1 well. Note thinning of the Red River section in this well (modified from Haidl et al., *in press).*

northwest-trending multistage salt-solution structures and major seismic positive elements (Kent, 1973). The northeast margin of the present-day salt dissolution edge of the Prairie Evaporite is subparallel to the northeastern edge of the Wyoming Province (Figure 2), as are surficial topographic lineaments formed by Wascana Creek, Moose Jaw Creek and Souris River waterways and the northeastern edge of the Missouri Coteau (Figure 5). The Elbow-Weyburn trend (Figures 2 and 5) of Paleozoic age is also oriented northwest-southeast (Christopher, 1980).

Wascana Creek, Moose Jaw Creek, and Souris River each have a U-turn which reverses their flow direction (Figure 5). These turns are located in or near a northeast- trending area that approximately aligns with the northeastern edge of Prairie Evaporite solution. Also, Moose Mountain Creek and Long Creek commence close to this area, in which the Minton, Ceylon, Cedoux, Tyvan, and Chapleau Lake Red River producing areas are situated. These and other Red River producing areas, and their correlation with regional lineaments interpreted from airphoto and satellite images, along with subsurface geological and geophysical data sets, have been recognized by Penner (in Mollard, 1999, Figure 31a).

Numerous authors have recognized Precambrian basement structural controls on sedimentation within the Williston Basin (Kent, 1973, 1974, 1987; Potter and St. Onge, 1991; Kissling, 1997). Some have described a predominance of lineaments with northeasterly and northwesterly strikes which they attribute to regional stresses in Precambrian basement rocks (Thomas, 1974; Bell and Babcock, 1986; Stauffer and Gendzwill, 1987; Brown and Brown, 1987; Penner and Mollard, 1991; Misra *et al*., 1991; Gibson, 1995). Some of these lineaments are recognized by surface structure, stratigraphic contacts, and geomorphic anomalies from air photos (Thomas, 1974), others by integrating a variety of data sets from geological, geophysical, geochemical, and hydrogeological sources (Brown and Brown, 1987; Mollard, 1988; Penner and Mollard, 1991). The dominant lineament trends in southern Saskatchewan are about N50°E, N50°W, N35°W, and N35°E (Penner and Mollard, 1991) (Figure 6).

Misra *et al.* (1991) employed remotely sensed Landsat MSS, TM, and Seasat satellite radar images to derive lineament maps. They found no obvious relationship between patterns found on regional magnetic maps and brittle fractures in Phanerozoic strata. They also mapped a ca.100 km wide northwest-trending linear feature, the Central Fault Zone (CFZ), extending from northern Alberta to the U.S. border southeast of Regina, and apparently defining the northeastern margin of the Wyoming Province in the basement of southeastern Saskatchewan.

Gerhard *et al.* (1991) related major faults and fault folds in the Williston Basin to a hypothetical Proterozoic wrench-fault system dominated by two major northeast-trending left-lateral, strike-slip fault zones (the Brockton-Froid-Fromberg and Wyoming-Colorado) (Figure 2). They suggested that: a) little evidence exists for Phanerozoic left-lateral motion along the two zones and b) the dominant movement in the Phanerozoic has been vertical.

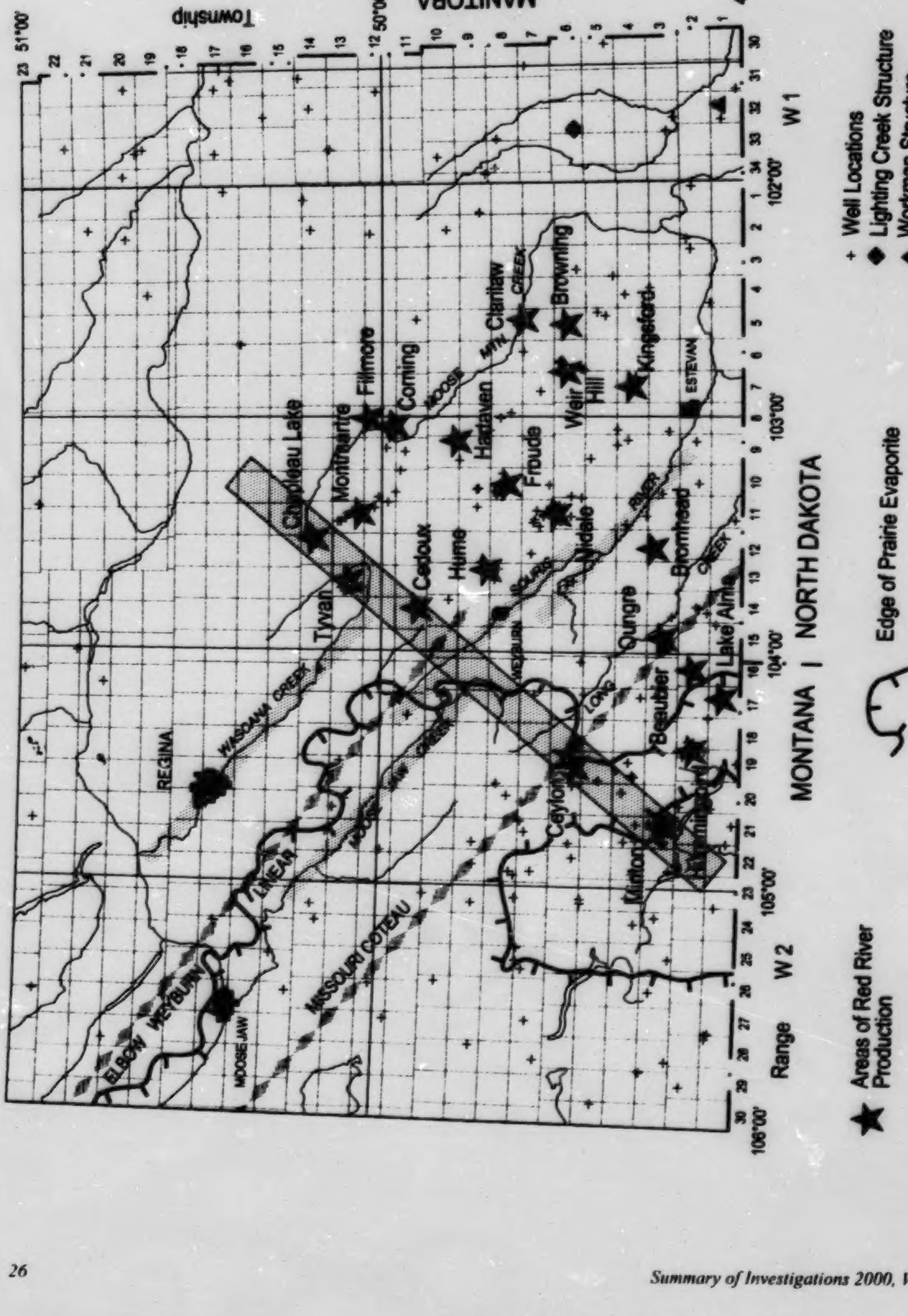

Figure 5 - Missouri Coteau, Elbow-Weyburn trend, and water drainage show a northwest-southeast orientiation. U-bends causing the Wascana Creek, Moose Jaw Creek, and Souris River to reverse their flow directions are located in or near a northeast-trending area indicated by dark grey shading. Also, Moose Mountain and Long Creeks rise close to this area.

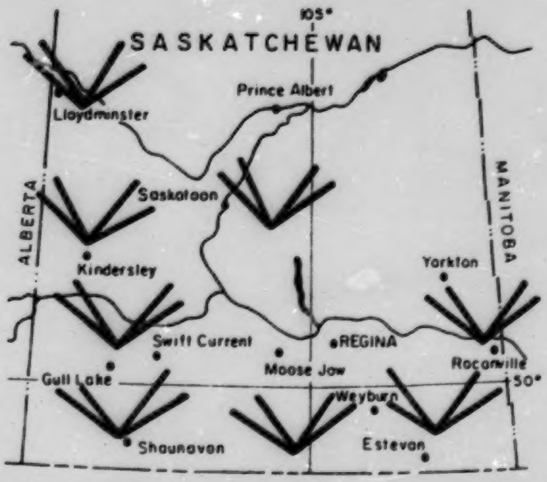

Figure 6 - Map of southern Saskatchewan showing double suborthogonal fracture lineament systems, indicated by heavy dark lines, from eight study areas (from Mollard, 1988).

Gough and Bell (1981), Bell and Babcock (1986), and Bell *et al.* (1994) believe that stresses causing breakouts in well bores across western Canada originate in the lithosphere. They determined that the maximum horizontal stress is oriented northeast-southwest and speculated that this anisotropy in the stress regime is the result of drag effects as the mid-American lithosphere is pushed northeastward by a rising mantle convection cell beneath western North America.

3. Local Basement Features

A province-wide Lower Paleozoic mapping project initiated by staff of the Petroleum Geology Branch of Saskatchewan Energy and Mines is complete. Structural and stratigraphic information from this mapping shows a spatial relationship between paleotopographic highs on the Precambrian crystalline basement and structural and thickness anomalies in overlying Lower Paleozoic strata such as the Deadwood and Red River formations (Figures 7 to 10). For example, the isopach map of the Deadwood Formation in southeastern Saskatchewan (Figure 7) clearly reflects areas of high relief on the Precambrian basement surface (Figure 9). A ca. 70 km long northeast-trending zone of thin Deadwood joining the Midale, Froude, Hartaven, Corning, and Fillmore areas (Figure 7) forms the longest Precambrian ridge-like feature discernible from current well control. These features are interpreted to be linear zones comprised of small fault blocks in an *en echelon* arrangement. Clastic sediments of the Deadwood Formation appear to have onlapped and infilled areas around Precambrian basement highs.

The Amerada Crown S AD 13-12-14-24W2 well is located over the highest known basement uplift, ca. 170 m, as determined from the Deadwood isopach map. The extent and configuration of this feature cannot currently be determined from mapping since no other nearby wells penetrate the Precambrian. A seismic structure map at the level of the sub-Mesozoic unconformity surface centred over this well (from Sawatzky in Holter, 1969) and recently processed gravity data in the vicinity define a feature about 5 km across (Miles *et al.*, 2000).

In the past few years, exploration companies have recognized that hydrocarbon entrapment in the deeper plays is mainly in small fault-bounded closures that are spatially related to underlying Precambrian highs (Haidl *et al.*, in press). They therefore attempt to drill over basement highs only, resulting in a biased distribution of well control. Nevertheless, we believe that sufficient control exists to outline some basement linear features that are likely to be fault controlled. We envisage that the relief along these Precambrian paleotopographic lineaments ranges from a few tens of metres to at least 170 m and is essentially continuous over distances up to ca. 70 km (Figure 11). Milkereit *et al.* (1995) described Precambrian basement features of similar dimensions in central Alberta, interpreted from deep seismic reflection data.

Pre-Deadwood differential erosion may have played some role in creating the paleotopography on the Precambrian basement in southeastern Saskatchewan. However, as most of the rock samples from both Precambrian highs and lows examined in this study appear to be lithologically similar (granitic in composition), most of the basement paleotopography is interpreted to be the result of movement along fault zones that were active prior to, during, and after Deadwood sedimentation.

A remarkable feature of the Deadwood isopach map in southeastern Saskatchewan is the northwest and northeast orientation of basement highs, defined by Deadwood isopach thins (Figure 12). This is strikingly similar to the orthogonal pattern of surface and subsurface lineaments described previously (Figures 2, 5, and 6), implying that the basement highs are genetically related to the lineaments, perhaps by a stress regime in the Precambrian basement that is periodically reactivated. The close proximity of anomalously high Precambrian basement in the Amerada Crown S AD 13-12-14-24W2 well with a reported site of a magnitude 5 (Richter Scale) earthquake may be evidence of such reactivation in recent times (Figures 7 and 13). Earthquake activity in this region is thought to be related to movement along faults between blocks of rigid basement. Mollard (1987) shows that the distribution of seismicity has northwesterly, northeasterly, and northerly trends (Figure 13). He also notes that the southwestward extension of the basement high trend in Figure 12 passes directly below an offset in the course of the Souris River (Township 5, Range 12W2) which is accompanied by a drop in base level (Figure 14), and suggests that these changes may be due to tectonism. This basement high trend is parallel to the Brockton-

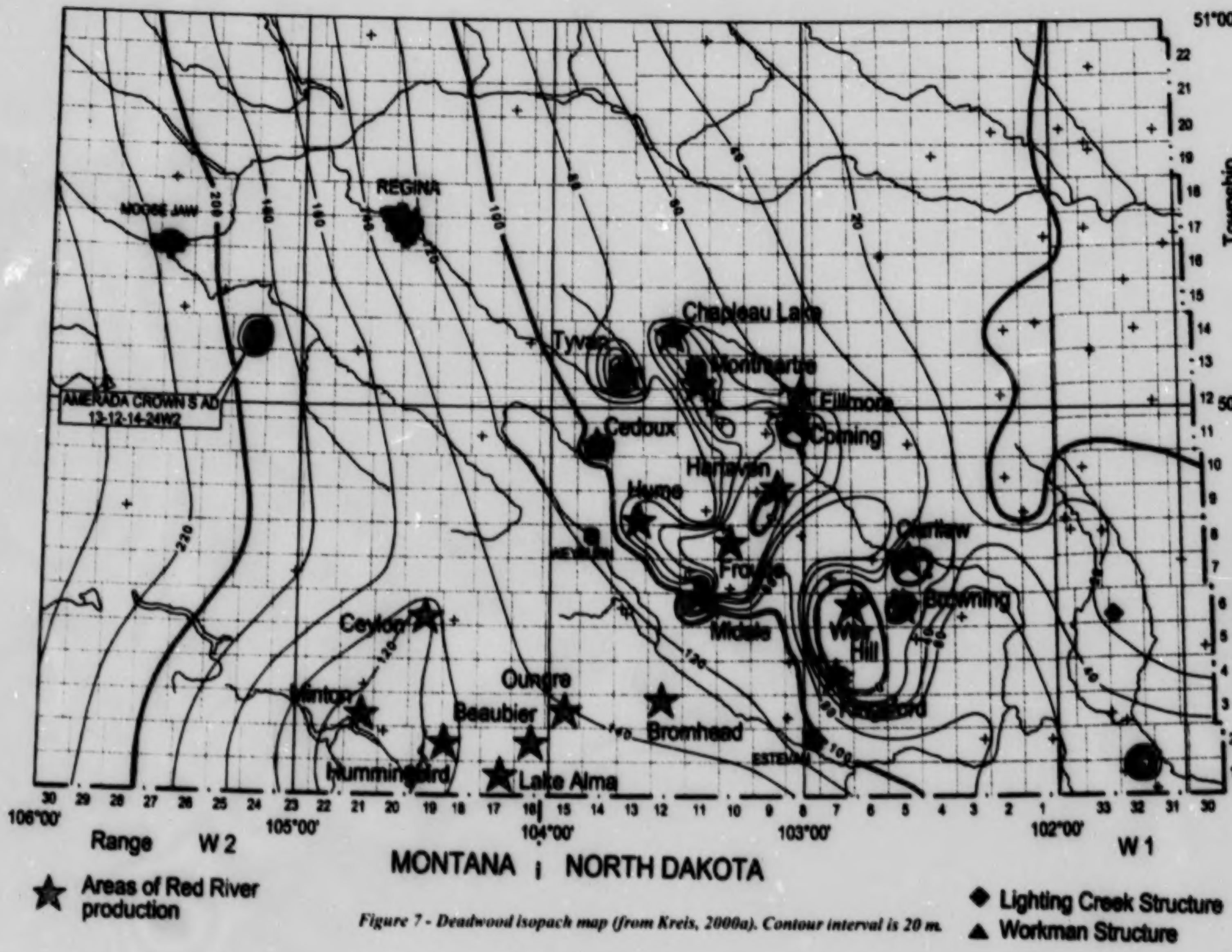

Figure 7 - Deadwood isopach map (from Kreis, 2000a). Contour interval is 20 m.

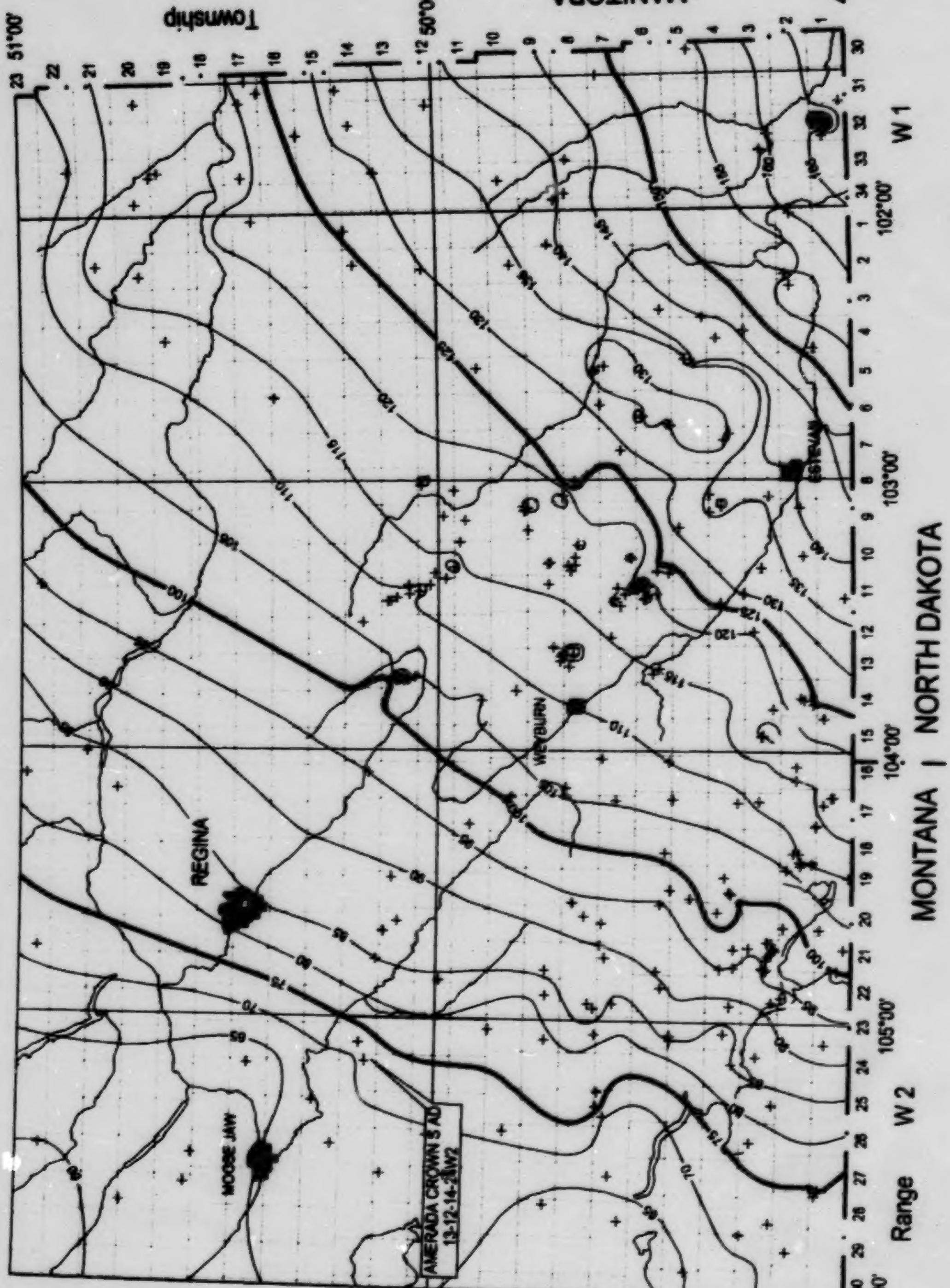

Figure 8 - Red River isopach map (from Kreis and Haidl, 2000). Contour interval is 5 m.

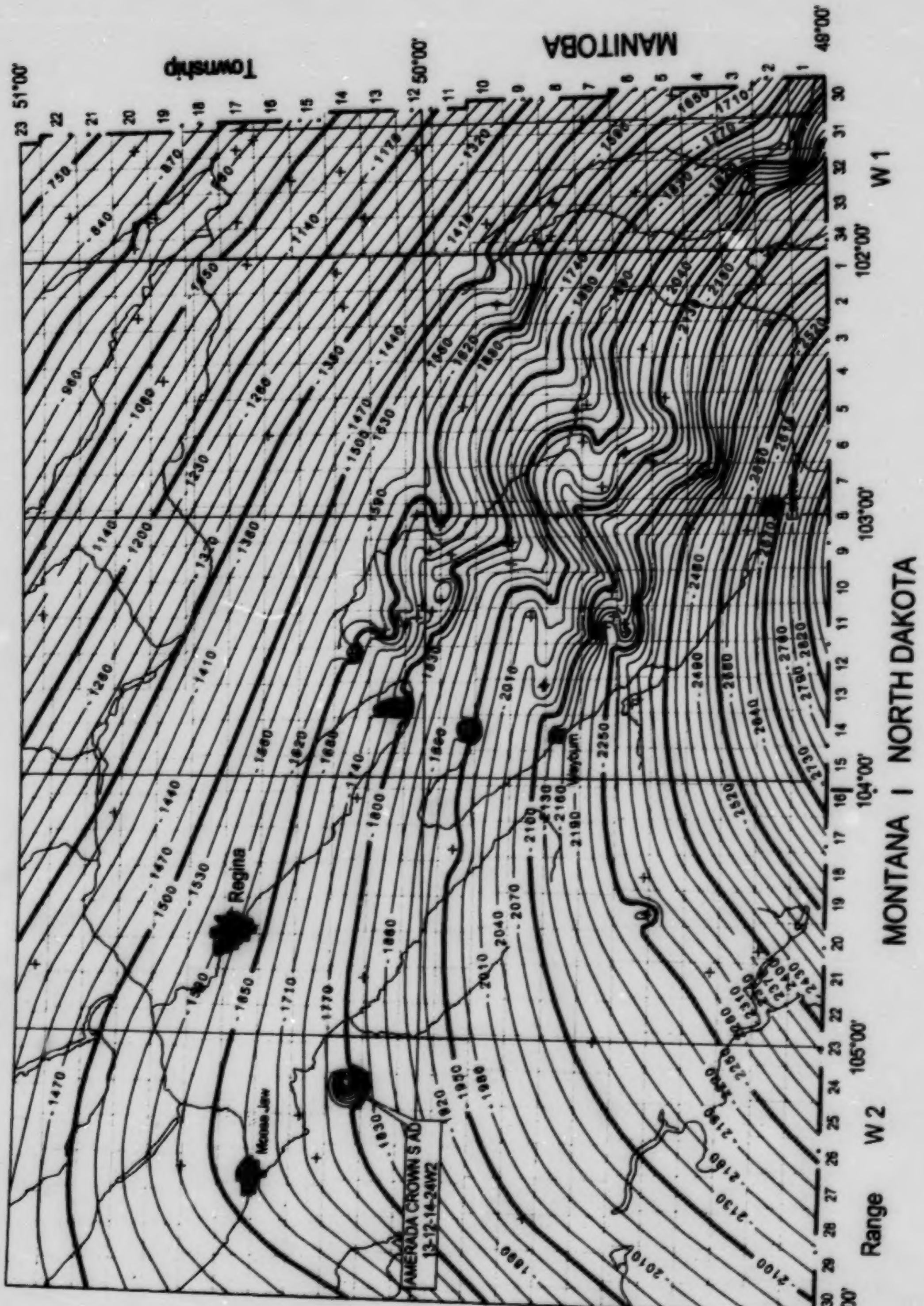

Figure 9 - Precambrian structure map (from Kreis et al., 2000). Contour interval is 30 m.

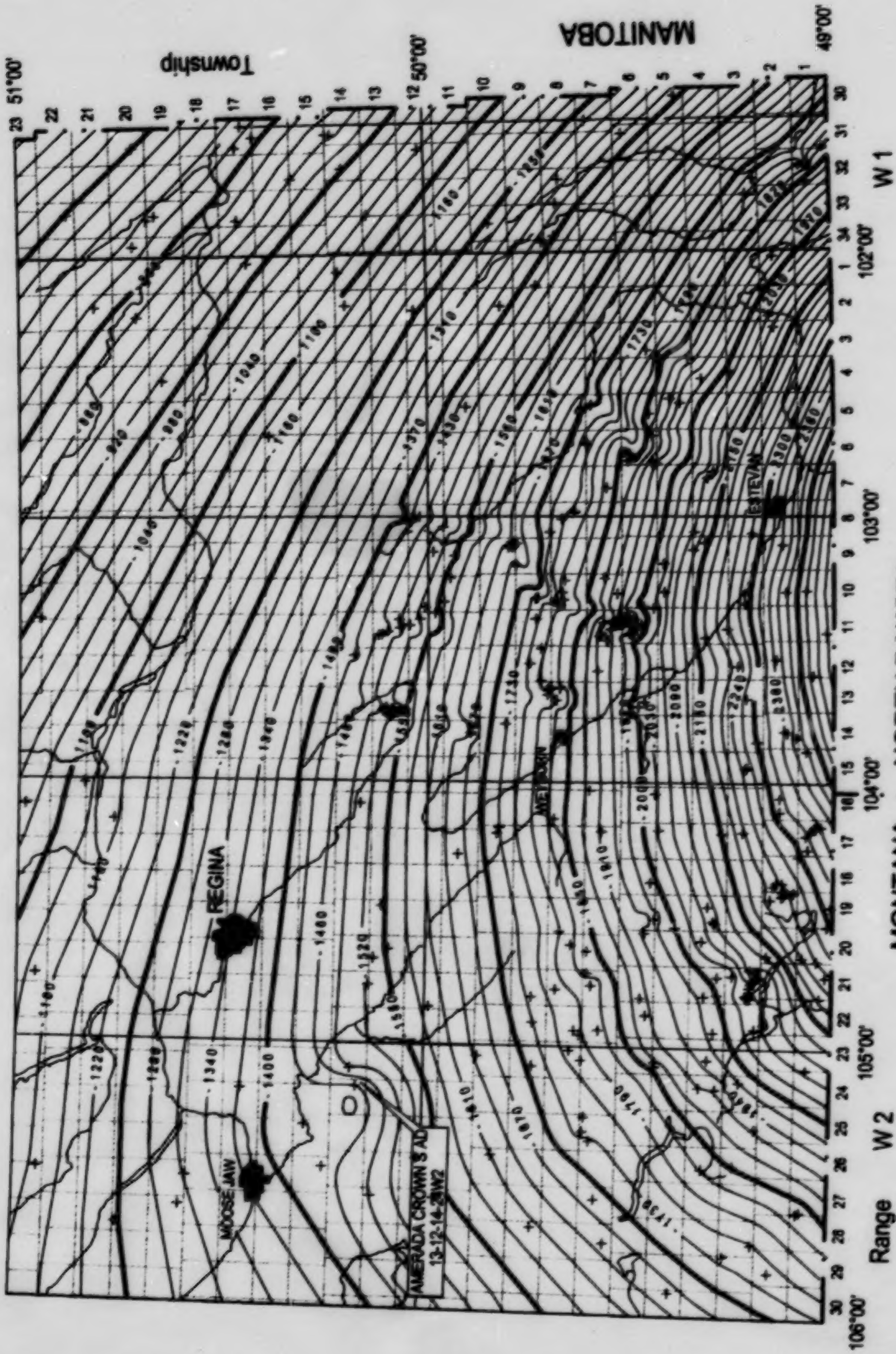

Figure 10 - Red River structure map (from Kreis and Haidl, 2000). Contour interval is 30 m.

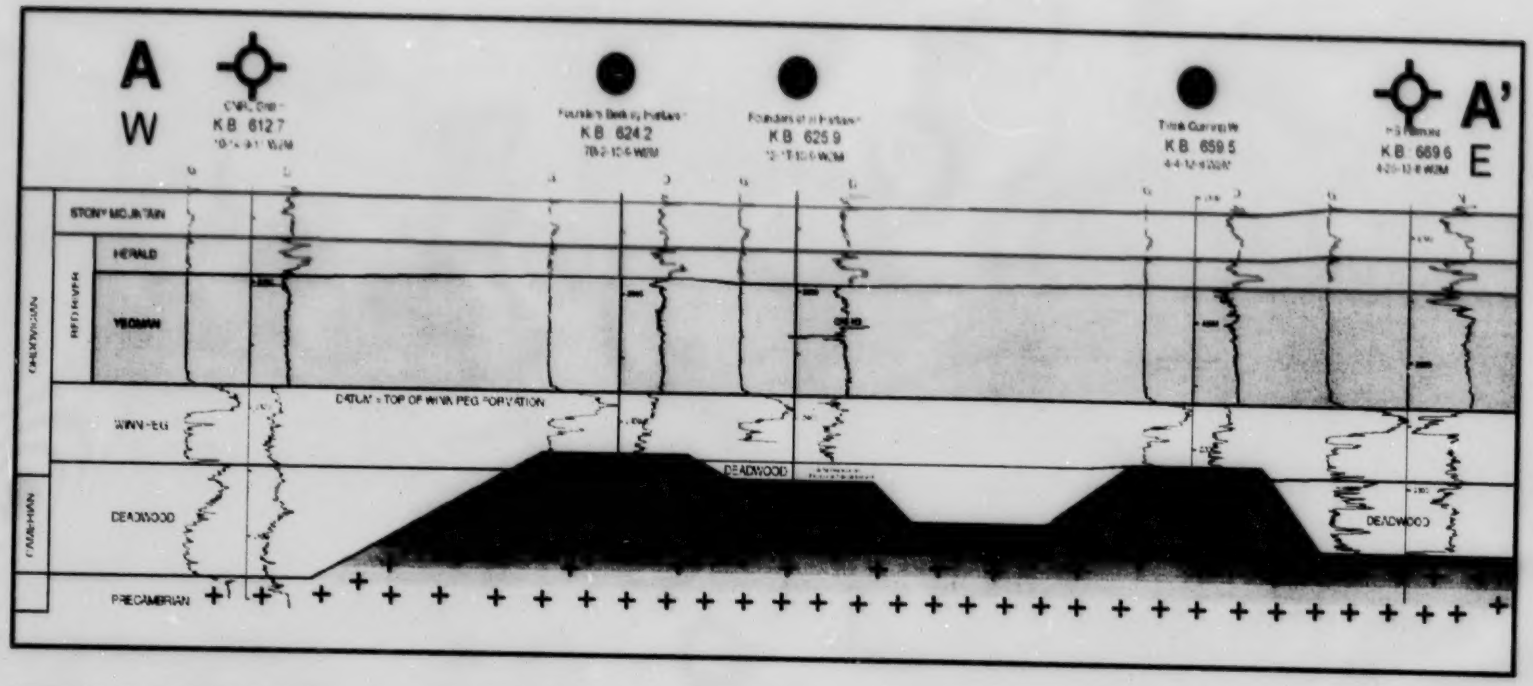

Figure 11 - Cross-section A-A' along axis of northeast-trending positive paleotopographic relief on Precambrian surface. Note that the 10-14-9-11W2 well is slightly off-trend (see Figure 1) and shows no relief on the basement (modified from Haidl et al., in press).

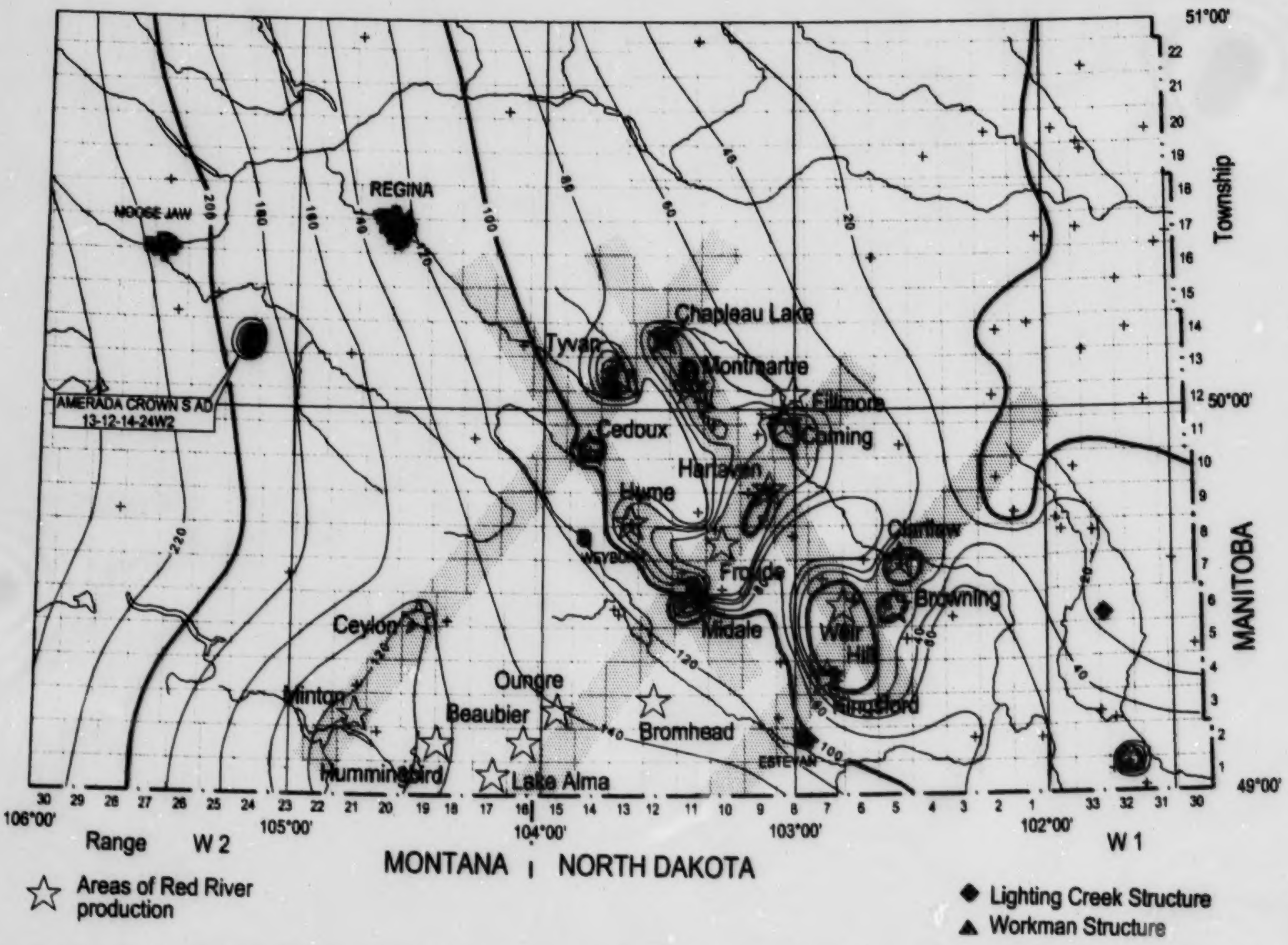

Figure 12 - Deadwood isopach map showing northeast- and northwest-trending elongate areas of thinning over basement highs. Note that many of the Red River pools are situated within these areas. Contour interval is 20 m.

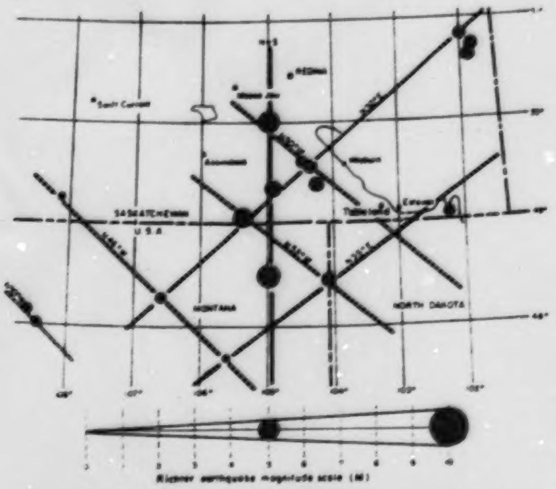

Figure 13 - Earthquake map showing northwesterly and northeasterly linear trends in the Williston Basin, southeastern Saskatchewan and the conterminous United States (from Earth Physics Branch, Canada Department of Energy, Mines and Resources, Victoria, British Columbia, 1977, in Mollard, 1987).

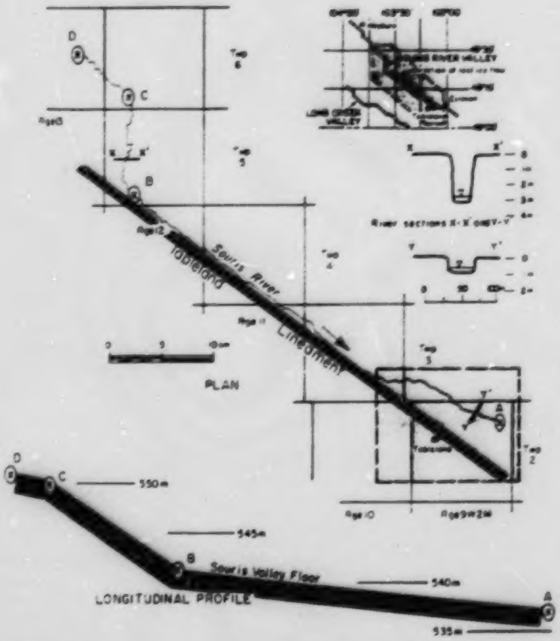

Figure 14 - Profile and plan views of part of the Souris River Valley showing changes in morphology, possibly related to active tectonism, west of Estevan, southeastern Saskatchewan (from Mollard, 1987).

Froid-Fromberg fault zone (Figure 2), implying they are genetically related.

4. Stratigraphy

In southeastern Saskatchewan, the basal unit of the Bighorn Group is termed the "Red River" and is formally subdivided into an upper formation, the Herald, and a lower, the Yeoman, (Kendall, 1976) (Figure 3). Where this subdivision cannot be recognized on geophysical logs, Red River Formation is used (Kreis and Haidl, 2000). In the U.S. portion of the Williston Basin (Figure 2), the term Red River Formation is used, and is further subdivided into drilling-based informal intervals called the "A", "B" and "C" in descending order (Longman and Haidl, 1996).

The Herald and Yeoman formations are Late Ordovician (Edenian, Maysvillian, and Early Richmondian) in age (Elias *et al.*, 1988; Norford *et al.*, 1994). In southeastern Saskatchewan, the Yeoman generally overlies shales of the Icebox Member of the Winnipeg Formation (Trentonian–Early Edenian). The nature of the contact is uncertain. Paterson (1971) interprets this contact to be erosional, at least in part, at the margins of the Winnipeg depositional basin. Other workers believe that the contact is conformable and merely represents a depositional hiatus (Vigrass, 1971; Ellingson and LeFever, 1995; LeFever, 1996; Kreis, 2000b). In extreme southeastern Saskatchewan, beds of calcareous shale belonging to the Roughlock Member, the uppermost member of the Winnipeg Formation, are less than 5 m thick. This unit thickens to the south into North Dakota (Figure 15). The Upper Ordovician Stony Mountain Formation (Late Richmondian in age) overlies, with nondepositional discontinuity, the Herald in southeastern Saskatchewan (Kendall, 1976).

The Yeoman Formation is made up of totally dolomitized, partially dolomitized and nondolomitized, burrow-mottled and burrowed but nonmottled, lime mudstones and wackestones with scattered packstone and grainstone lenses of skeletal debris (Porter and Fuller, 1959; Kendall, 1976; Canter, 1998; Kent and Haidl, 1999). The skeletal debris most commonly observed in core is brachiopod valve fragments, crinoid columnals, and scattered solitary rugose corals. Much of the debris is so finely comminuted that it is only recognizable in thin section. However, recent cores of the Yeoman from the Tyvan, Montmartre, and Chapleau Lake areas have much coarser skeletal debris including hormotomid and bellerophonid gastropods, catenoporid and favositid corals, well preserved brachiopod valves, and orthocone fragments. In general, the Yeoman can be subdivided into a lower interval mainly made up of limestone and an upper interval, variably composed of limestone and dolostone. According to Kent and Haidl (1999), the upper Yeoman is predominantly dolostone east of a line running from 17-32W1 to 1-10W2. West of that line, within the study area, apart from a few exceptions such as the Husky Cedoux 5-11-11-14W2 well in which the upper interval is totally dolomitized, the upper Yeoman has alternating limestone and dolostone intervals. Favourably dolomitized zones in this upper interval are the primary oil reservoirs in Yeoman rocks in southeastern Saskatchewan.

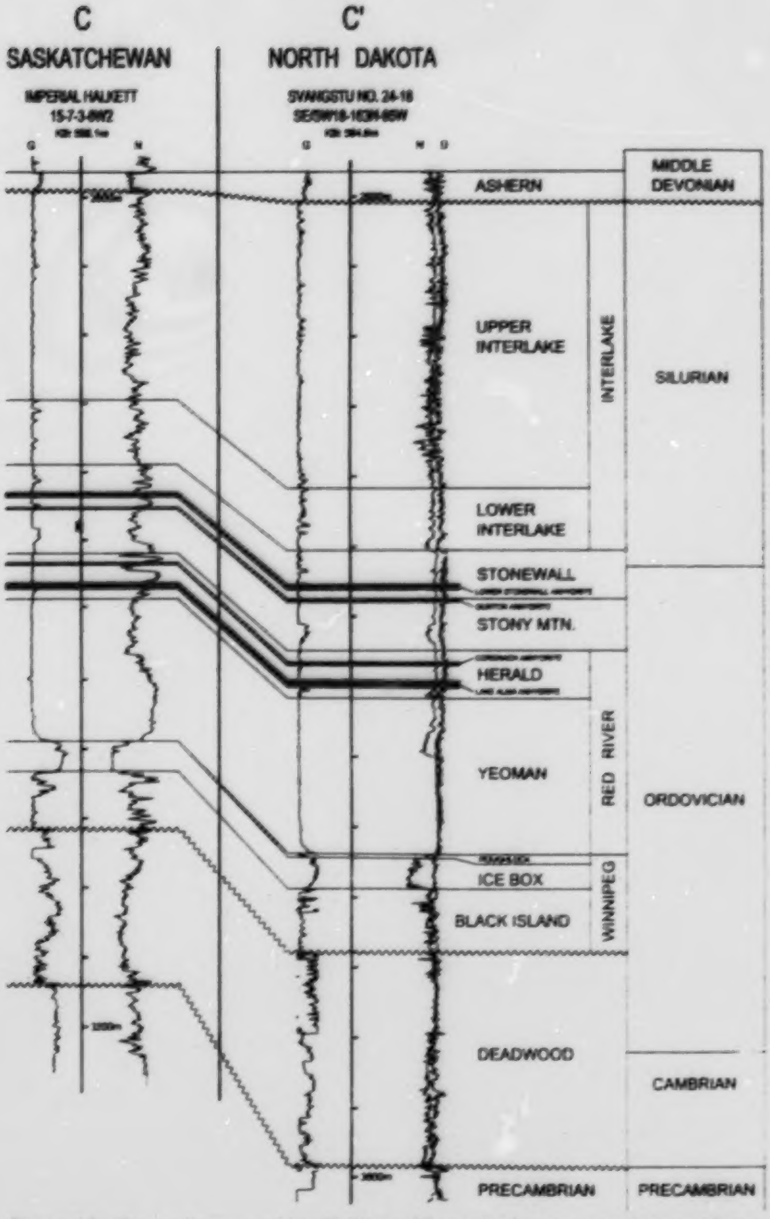

Figure 15 - Two well cross-section C-C' (see Figure 1) showing correlation of Lower Paleozoic strata between southeastern Saskatchewan and northwestern North Dakota.

The Herald Formation is composed of limestones, dolostones, and evaporites. It is subdivided in ascending order into the Lake Alma and Coronach members and the Redvers unit (Kendall, 1976). The Lake Alma Member is lithologically the most varied unit of the entire Red River succession. It includes an upper anhydrite, the Lake Alma Anhydrite, a medial laminated to bedded dolomitic unit, the "C" Laminated, and a basal interval with a variety of carbonate facies.

The basal interval of the Lake Alma Member is not easily identified on geophysical well logs but is recognizable in core. Kent and Kissling (1998) demonstrated that it contains significant facies variations, which they considered to represent pronounced shallowing of the below-fair-weather wave base conditions that prevailed during Yeoman time. They defined four basic facies – oolitic shoals, stromatoporoid-microbialitic banks, shallow-water open-marine, and tidal flats – using textural, biotal, and allochemic criteria (Figure 16).

The oolitic shoals are composed of dolo-packstones and dolo-grainstones of 0.15 to 0.5 mm, ovoid to elongate, ooids with single outer cortices coating pale yellowish grey dolomicritic nuclei. The thickest deposits of ooids lie along 102°W where they reach almost 3 m in thickness. Elsewhere beds are seldom more than 0.5 m thick and are commonly interlayered with 0.1 to 0.2 m thick oolitic and skeletal wackestones and wackepackstones. The skeletal debris mixed with the ooids is thin-shelled brachiopod valve fragments and crinoid columnals with rare calcareous algae disks and ramose bryozoan fragments.

The stromatoporoid-microbialitic bank facies is best developed in the LVR et al. Steelman 7-28-4-4W2 well where the sequence comprises: 1) a rudstone unit (4.4 m thick) dominated by laminar stromatoporoids; 2) a reefal boundstone (2.8 m thick) composed primarily of "digitate and locally crust-like 'thromboids' of microbial origin"; and 3) two thin (each less than 1 m) skeletal beds which were deposited at the top of the sequence, and between the rudstone and the overlying microbial boundstone (Pratt *et al.*, 1996). In addition to laminar stromatoporoids and thromboids, fossil components include domical stromatoporoids, crinoid columnals, trilobite and brachiopod fragments, rugose corals, ostracodes, ramose bryozoans, gastropods and calcareous algae *(Ortonella)*.

The shallow-water, open-marine rocks are dominated by skeletal and/or *Planolites*-burrowed dolomicrites

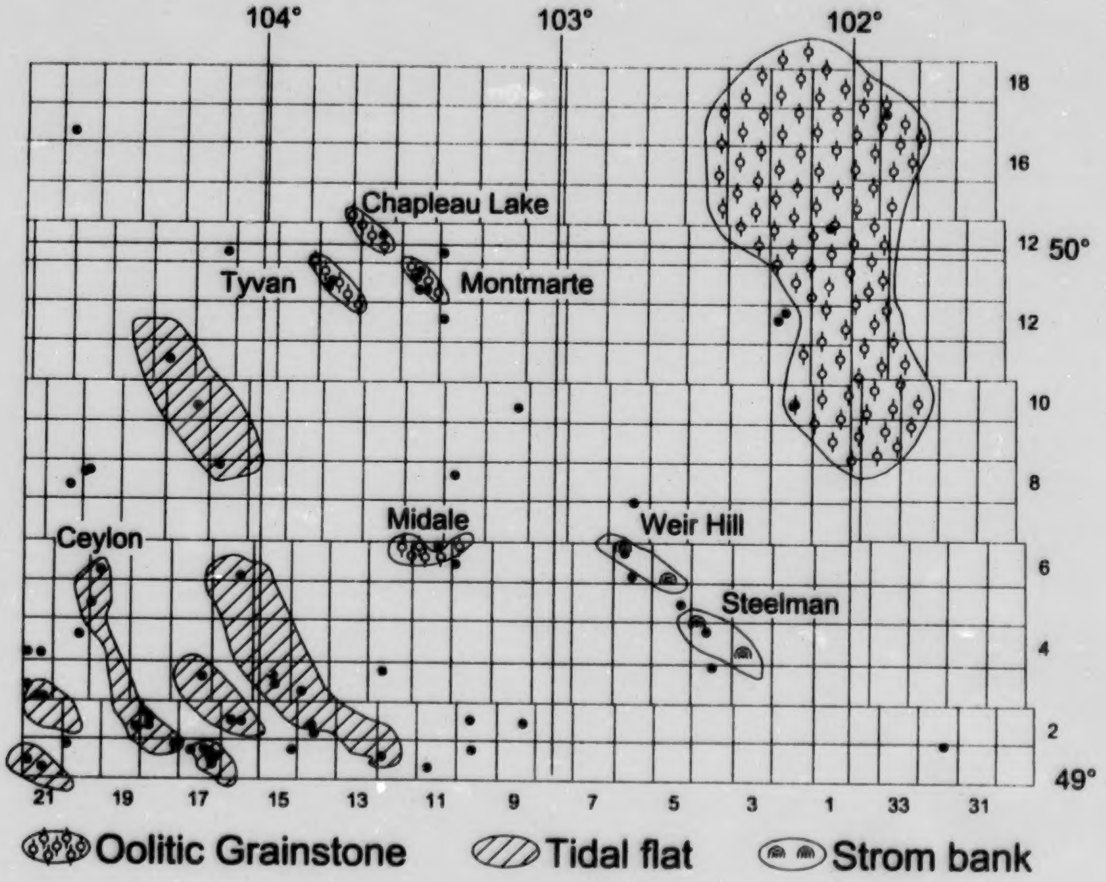

Figure 16 - Basal Lake Alma facies map.

and dolo-wackestones with, in places, fining-upward intervals of dolo-packstone and dolo-grainstone. The skeletals include crinoid columnals, solitary coral debris, brachiopod valve fragments, broken ramose bryozoa, wafer-like fragments of stromatoporoid, and oncolite-coated nautiloid debris. Between the oolitic shoals, the open-marine sediments are commonly disturbed and distorted dolomicrites with pods and streaks of ooids.

Tidal-flat deposits are represented by alternating light- and dark-coloured, planar, wavy and crinkly laminated dolomicrites in which some of the laminae are discontinuous whereas others appear to have been broken into granule- and pebble-size clasts. Some laminae have planar surfaces, others have wavy upper or lower surfaces. Bulges on an upper surface of one lamina are commonly compensated for by indentations in the bottom surface of the overlying layer. These rocks are similar to those illustrated by Demicco and Hardie (1994) and interpreted to have had a tidal-flat origin.

The "C" Laminated interval of the Lake Alma Member is both laminated and thinly bedded. Hairline solution seams commonly accentuate the interlaminar surfaces and bedding planes. In places, the laminations are stromatolitic in appearance. Elsewhere, sharp discontinuities are present, above which are elongate, flat intraclasts. Most layers are made up of extremely finely crystalline dolomicrite sufficiently dense that conchoidal fractures are produced on broken surfaces. Ostracod remains are generally the only fossils found, but typical stenohaline biota have been seen in a few widely distributed cores, including crinoid columnals, brachiopod valve fragments, solitary rugose corals, bryozoans, and calcareous algae disks.

The generally dense character of the "C" Laminated gives the rock poor reservoir potential, but one of the most prolific oil producers of the pre-1995 wells, CDR S Lake Alma 1-14-1-17W2, produced from this unit. In addition, Tri-Link Tyvan 10-17-13-13W2 is strongly oil-stained in the "C" Laminated which here appears to be the best interval for potential hydrocarbon production. Thin-section studies by Kent and Haidl (1999) show the dolomite of the reservoir rock in 1-14-

1-17W2 is more coarsely crystalline than normal. Kent (1997) records the presence of highly dolomitized skeletal debris in the thin sections which could account for the coarser crystallinity of the dolomite.

The Lake Alma Anhydrite is equivalent to the "C" Anhydrite in the U.S. part of the Williston Basin. It is the most extensive of the evaporites found in the Herald Formation. In Canada, it extends a few ranges into Manitoba, as far north as Township 33 and to Range 10W3 in western Saskatchewan (Kent, 1960; Kendall, 1976; Norford *et al.*, 1994; Kreis and Haidl, 2000). The Lake Alma Anhydrite is partially or totally cored in 20 wells. Its contact with the overlying Coronach Member is generally placed at the base of a thin laminated dolomicrite which passes upward into the nodular limestones of the basal Coronach. In places, the laminated dolomicrite is absent and the contact is at the base of the limestone. On geophysical well logs this contact is located at the base of a slight increase in the gamma-ray signature.

The Lake Alma Anhydrite typically has a layered appearance due to either interlaminated anhydrite and dolomite or inherent bedding in the anhydrite. Where dolomite is present, it may be in the form of discrete millimetre-thick laminae or discontinuous streaks. In several cored wells the evaporite is split into two anhydrite intervals by about a metre of laminated dolomicrite, and the lower portion is nodular rather than layered.

The Coronach and Redvers are equivalent to the "B" and lower "A" zones in the U.S. portion of the Williston Basin (Figure 3). To date, neither of these units is considered to have much hydrocarbon-producing potential in Saskatchewan. However, in light of exploration successes in the "B" zone of Bowman County, North Dakota, and the Buffalo Field, South Dakota, they should not be totally overlooked. Also, scattered oil shows occur in the Coronach Member in some of the 17 cores in southeastern Saskatchewan. In eight of these cores, the complete Coronach succession is present. The Redvers is fully cored in four wells and part of it is present in another three cores.

The Coronach-Redvers contact is intersected in nine cores, in four of which it is easily determined as it is placed at the top of either the Coronach Anhydrite or a patterned carbonate above the evaporite. The evaporite is absent or poorly preserved in five cores, and the contact is placed at a sharp, readily recognizable bedding surface that is overlain by an intraclastic breccia. No obvious brecciation is present in the fifth core in which the contact is located at the top of a bedded to laminated dolomicritic interval. On geophysical logs, the contact is placed at the base of an increase in gamma radiation that, in places, shows as a sharp positive deflection of the gamma-ray curve about 3 to 5 m below the base of the Hartaven Member of the Stony Mountain Formation. Aside from the thinly laminated dolomicrite at its base and a thinly layered anhydrite at the top, the Coronach is composed of two other lithologies, a lower skeletal lime mudstone to wackestone and an upper dolomicrite. The skeletal lime mudstone to wackestone is poorly to non-stratified, dominantly cryptocrystalline, but in places microcrystalline, limestone with abundant solution seams and rare burrow and burrow-halo networks. The main allochems are crinoids, brachiopod and ostracod valve fragments, and rugose corals. Where it is cored, the dolomicrite is similar to the "C" Laminated, and varies from laminated to thinly and thickly bedded. Elsewhere, the dolomicritic interval also has some well developed stromatolites, particularly close to the stratigraphic level of the Coronach Anhydrite. The entire Coronach section is dolomitized in two cores. In other cores, only the dolomicrite and the upper few metres of the skeletal lime mudstones and wackestones are dolomitized.

The Redvers unit is dominantly bedded to laminated, poorly fossiliferous lime mudstone and dolomicrite. It is, however, markedly different in core from CDN-DEV TW Langbank 15-28-12-2W2, where it is a brachiopod-rich wackestone with a thin oolitic grainstone at the base.

5. Depositional History

The Upper Ordovician Red River strata of the Bighorn Group record deposition of marine carbonate rocks in a clear-water sea. The basal contact between the marine carbonates of the Yeoman and the underlying marine shales of the Winnipeg is relatively sharp, suggesting a rapid change in the depositional regime of the Williston Basin during this transition. The monotonous succession of burrow-mottled and mainly lime mud-supported sediment implies low-energy conditions through most of Yeoman time, but, in places, thin storm sheets made up of skeletal grainstones and packstones punctuate the succession and are indicative of intermittent higher energy conditions. The presence of horizontal to oblique burrow mottles in the Yeoman Formation suggests the sediments were below fair-weather wave base (Kendall, 1976). An apparent lower diversity of biota in the Yeoman in southeastern Saskatchewan than in east-central Saskatchewan and western Manitoba led Kendall (1976) to argue that deeper water conditions prevailed there. He supported his proposal with reported occurrences of ripple marks and desiccation cracks in the Red River outcrops of east-central Saskatchewan. If his argument is valid, slight increases in biotal diversity in the Yeoman reported for the Montmartre and Tyvan areas may indicate local shoaling in southeast Saskatchewan.

The basal Lake Alma represents shallowing prior to restriction of the sea, leading to the accumulation of penesaline rocks of the "C" Laminated and the hypersaline Lake Alma Anhydrite. The normal-marine, shallow-water setting represented by the thin basal Lake Alma rocks presents the most varied facies relationships found in the Bighorn Group. The overlying Coronach replicates the Yeoman–Lake Alma succession except an equivalent to the basal Lake Alma interval is absent. The top of the Coronach may represent an important hiatus. Intraformational breccias are present in four wells, two of which are in the Midale area, that intersect the Coronach-Redvers contact. This contact in one of the Midale wells, 12-2-7-11W2, is an irregular surface underlain by a mosaic breccia of flat clasts 0.1 to 1 cm in diameter. It is overlain by ovoid, rounded clasts of similar diameter to those in the mosaic breccia supported in an argillaceous dolomicritic matrix. The combination of mosaic breccia in the rocks underlying the contact and the irregularity of the surface suggests a possible subaerially exposed surface. The Redvers is predominantly laminated to bedded and may represent a penesaline environment similar to that represented by the laminated facies near the base of the Lake Alma.

6. Structural Controls on Sedimentation

Kent (1987) compiled information about structural controls on sedimentation from many sources. He used localized thinning and thickening of marker-defined intervals as evidence for syn-depositional tectonic activity. He also identified localities where anomalous occurrences of rocks that were originally deposited in shallower or deeper water could be attributed to seafloor features resulting from synsedimentary structural up- or down-warping. Similarly, this study attempts to identify structurally controlled sedimentation in the Bighorn Group. The shallow-water sediments of the basal Lake Alma are an obvious interval to study for anomalous facies developments as they would have more sensitively reflected bathymetric changes than the deeper water sediments of the Yeoman. Anomalous facies developments coincident with anomalous thinning or thickening of a stratigraphic interval provide evidence for syn-depositional structural control (neither criterion alone is firm evidence for such control).

Three of the maps presented here are significant to this study. The Deadwood isopach map (Figure 7) and the Precambrian structure map (Figure 9) demonstrate the existence of Precambrian basement paleotopographic highs in southeastern Saskatchewan. The Red River isopach map (Figure 8) shows thinning over some of these features, a commonly recorded characteristic elsewhere in the basin (Byrd, 1978; Martens, 1978; Mueller and Klipping, 1978; Sharp, 1978). This thinning can be attributed to syn-depositional upward movement of the reactivated basement highs. The basal Lake Alma in core from wells located over basement highs in the Chapleau Lake, Tyvan, Montmartre, and Midale areas is made up of oolitic dolo-grainstones and dolo-packstones (Figure 16). Stromatoporoid-microbialitic banks occur over a high in the Weir Hill area, as do parts of tidal-flat complexes in the Ceylon area (Figures 1 and 16). In contrast, basal Lake Alma cores from wells that are close to, but not over basement highs, have ooids in dolo-wackestones and dolomicrites. From more distally located wells, they are generally skeletal wackestones and lime mudstones. Yeoman wackestones containing favositid and cateniporid corals and thick-shelled, robust brachiopods in core from Chapleau Lake, Tyvan, and Montmartre may also subtly reflect shallower seafloor at these localities. The biota contrast with thinner-valved brachiopods and an absence of colonial corals in Yeoman cores taken at some distance from the highs. A possible subaerial exposure surface is present at the top of the Coronach in Midale 12-2-7-11W2, also located over a basement high.

Not every basement structure was reactivated during the time of Bighorn deposition. This is shown by the presence of highs over which the Red River is not anomalously thin. At these locations, basal Lake Alma lithotypes are typically dolo-wackestones and dolomicrites with thin-valved brachiopods. Also, not all localities with thin Red River have high-energy lithotypes. For example, cores from wells in the area covered by Townships 1 to 12 and Ranges 12 to 21 west of the second meridian have tidal-flat rocks in the basal Lake Alma. Nonetheless, the occurrence of grainstones and packstones in basal Lake Alma cores commonly suggests an underlying basement high.

The localized nature of oolite occurrences at Chapleau Lake, Tyvan, Montmartre and Midale questions the existence of the extensive oolitic shoal identified by Kent (1960) and Kendall (1976) in an area close to 102°W. Oolite grainstones in cores from this area can alternatively be interpreted as being located on isolated, structurally positive features. As a broad regional Precambrian high (Figure 7) appears to be present, however, we prefer the extensive oolitic shoal interpretation (Figure 16).

7. Economic Considerations

To date, all Red River hydrocarbon production in southeastern Saskatchewan appears to be underpinned by Precambrian basement with measurable positive paleotopographic relief. Producing wells which penetrate the basement invariably show some thinning or complete absence of the overlying Deadwood Formation. The assumption therefore appears reasonable that wells which do not penetrate the Precambrian, but show Red River hydrocarbon entrapment, are likely to overlie a basement high. The apparent orthogonal arrangement of basement highs recognized from isopach mapping of the Deadwood and similar patterns from lineament mapping may prove useful as trend indicators for future plays of this type.

Generally, structural highs on the Precambrian surface (Figure 9) show up as structural highs on the top of the Red River (Figure 10) suggesting a genetic relationship. Also, hydrocarbon production is generally greater over the structurally highest Red River locations which tend to coincide with relatively higher paleotopographic relief on the basement. Bearing this in mind, the Amerada Crown S AD 13-12-14-24W2 well location, which shows the highest positive relief on the Precambrian basement yet recognized from mapping in southeastern Saskatchewan, is highly prospective (Figures 7, 9, and 10). The Yeoman portion of the Red River was not drillstem tested in this well, and evaluations of the SP, resistivity, gamma-ray and neutron logs taken in 1958 are inconclusive. Cores were not taken but cuttings show some zones of porosity and oil stains within the Stony Mountain Formation and the upper portion of the Yeoman Formation. Fluorescence micro-spectrometry studies suggest that the stains contain 30° to 35° API oil. Optical data from reflectance and fluorescence analysis of macerals in kukersitic source rock intervals associated with the stained cuttings show that the macerals are thermally immature to marginally mature. The oil found in this well has, therefore, probably migrated from a mature, downdip source (L.D. Stasiuk, pers. comm., 2000).

Kent (1973), using the isopach map from Ballard (1969), recognized that most Ordovician producing areas from the U.S. portion of the basin were associated with anomalously thin Upper Red River strata. This is also demonstrated by Byrd (1978), Martens (1978), Mueller and Klipping (1978), and Sharp (1978). Recent mapping further corroborates this association. The Red River also shows subtle thinning in the Amerada Crown S AD 13-12-14-24W2 well (Figure 8), suggesting the prospect of a nearby trap.

Identification of concentrations of oolitic or stromatoporoid-microbialitic bank facies in wells that do not penetrate Precambrian basement might be indicative of an area close to or overlying a Precambrian basement high. A secondary indicator may be the presence of coarse skeletal remains of catenoporid or favositid corals, thick-shelled brachiopods and high-spired gastropods. Recognition of these basement features may help focus exploration efforts.

Basement features have been linked to heat flow and electric conductivity anomalies in southeastern Saskatchewan (Majorowicz *et al.*, 1988). Improved knowledge of these anomalies and their apparent source in the Precambrian basement will enhance our understanding of the thermal maturation, migration and accumulation of Red River and other oils in southeast Saskatchewan. Exploration successes in the Red River and the Winnipeg Formation over the past few years should provide an economic incentive to pursue this work.

8. Future Work

Staff of the Petroleum Geology Branch, in collaboration with colleagues from the Northern Geological Survey Branch of Saskatchewan Energy and Mines, plan to continue investigating the sub-Phanerozoic Precambrian basement and its features. They have recently completed regional subsurface mapping of the province's Lower Paleozoic formations and will next map the Devonian strata.

9. Acknowledgments

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An Investigation into Microfloral and Floral Extinctions at the Devonian-Carboniferous Boundary

Peter Wagner [1]

Wagner, P. (2000): An investigation into microfloral and floral extinctions at the Devonian-Carboniferous boundary; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

1. Introduction

The aim of this ongoing palynological study is to investigate microfloral trends at the Devonian-Carboniferous (D-C) boundary in order to determine whether or not a 'mass extinction event' occurred. Global events detectable in the eustatic sea level curve are responsible for regionally widespread lithological changes at the time of the D-C boundary. Biostratigraphically, the D-C boundary is generally recognized by the disappearance of the plant spore *Retispora lepidophyta* (marking the boundary of the miospore zones LN and VI) and, in suitable marine lithofacies, by the first appearance of the conodont *Siphonodella sulcata*. Analysis of the extensive literature covering the stratigraphic distribution of plant mega- and microfossils clearly suggests that many land plants and the vast majority of acritarch (phytoplankton) taxa became extinct at or immediately below the D-C boundary. Evidence from earliest Carboniferous rocks suggests that the surviving Devonian land plant taxa were only slowly joined by newly evolving forms whereas the acritarch diversity remained very low throughout Carboniferous time. Widely differing practices, in terms of palynomorph classification, nomenclature, and method of reporting, however, have resulted in considerable confusion in the literature concerning the *true* turnover of taxa at the D-C boundary, especially so in the case of plant miospores and acritarchs.

A review of all recorded palynological taxa in latest Devonian and early Carboniferous rocks is being undertaken in order to determine the actual turnover of taxa at the D-C boundary and any regional trends developed. The miospore and acritarch taxa being reviewed will help resolve the synonymies that severely limit the value of the literature. The data are being compiled in a database to enable efficient exchange and analysis of the biostratigraphic data generated.

Selected rock sections spanning the D-C boundary are being investigated in Europe and North America in order to: 1) provide well-preserved palynomorph assemblages as the basis for the taxonomic studies, and 2) assess any changes in absolute yields of palynomorphs from sections representing similar depositional environments. Standardized preparation techniques are being employed, including addition of a *Lycopodium* 'spike' to weighed samples.

2. Progress To Date

a) Fieldwork

To date about 130 samples have been collected from localities in southern Ireland, Portugal, Ohio (USA), and Saskatchewan (Canada). The sections sampled are listed below. They span the D-C boundary at localities known from previous studies to contain adequate palynological assemblages.

1) Hook Head, Ireland, is a prime location for larger miospores and megaspores; a well-preserved and diverse assemblage was recovered from the uppermost Old Red Sandstone and overlying lithologies.

2) The uppermost Famennian and lowermost Tournaisian rocks were sampled in the South Portuguese Zone. The Pedra Ruiva Sul, Pedra Ruiva Norte, and Monti di Penedo sections should yield samples from both the LN and VI biozones. Additional samples of the LN biozone were collected at Vale Figuera and Ribeira da Malhadas. Both sections consist of dark mudstones with thin interlayers of sandstone. The lithology of Vale Figueras shows calcareous input, which could be interpreted as a primary lateral facies change or a result of secondary rock alterations. The consequent differences in preservation of the fossil record, therefore, could be either depositional or taphonomic.

3) In Ohio (USA), the Ohio Shale, the Bedford Shale, the Berea Sandstone, the Sunbury Shale, and the Cuyahoga Formation were sampled. The D-C boundary has been placed between the Berea Sandstone and the Sunbury Shale. The Berea Sandstone is cross-stratified and displays large-scale channeling. Only the lowermost part of the formation contains lithologies worth sampling for palynomorphs. As neither the time span of deposition of the Berea Sandstone, nor the duration of the pre-Sunbury hiatus is known, these samples will yield insight only into the LN or VI assemblages, rather than give detailed information about the transition from the Devonian to the

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Carboniferous. Prior work recovered sufficient numbers of acritarchs, however, to make these assemblages highly valuable for the aims of the project. Localities sampled were the Tener Mountain roadcut section in southern Ohio, the Three Locks Road abandoned quarry at Columbus, a cliff along the river at Sunbury, a roadcut in the Community Park in Berea, and the Granger Road abandoned quarry and Brooklin Height Park in Cleveland.

4) In Saskatchewan, Canada, samples were collected from core stored at the Subsurface Geological Laboratory of Saskatchewan Energy and Mines. The core from A7-34-29-24W3 represents the Bakken Formation, comprising basal dark shales, medial sandstones interlayered with silt- and mudstones, and capping black shales. The D-C boundary is probably below the upper shale member although there is some discussion about conflicting microfloral evidence that is possibly caused by reworking of index fossils. Nevertheless, the interlayering of the lithologies makes this formation a premier candidate for investigations on the D-C boundary.

5) The lateral equivalent of the Bakken Formation of the Williston Basin is the Exshaw Formation in the Rocky Mountains. Outcrop material was collected directly below and above the assumed D-C boundary at the type location of the formation.

b) Palynology

Detailed palynological studies of the samples taken at Hook Head are in progress along with taxonomic investigation and reviewing of the synonyms. Also, samples collected in Canada are being processed in order to start the palynological investigation.

c) Data Processing

A database of existing literature has been established with several hundred related entries and over 100 directly relevant listings. Also, an overview of palynomorph genera and species has been compiled from existing commercial databases and literature. These two lists have been combined into an index of the literature on certain taxa. This makes taxonomic work by genera effective and quick. The database will continue to be expanded.

Development of these data sets precedes that of an integrated and interpretative "D-C Palynotaxa Database", constructed in FILEMAKER PRO, a commercially available program for PC and Macintosh platforms. This program is easy to use and will facilitate modification of the database by co-workers in the project and other users.

D-C Palynotaxa Database is designed to make regional and time-related changes in the community of microfossils visible especially in the LN and VI biozones. It contains the following 12 data fields: Palynomorph Type, Genera, Genus Definition, Species, Species Descriptions, Pictures, Library, Region, Localities, Locality Maps, Occurrences, and Assemblage. Information overlap between data fields is kept to a minimum, and data are limited to the essential in order to make usage easier. To gain additional information on certain topics the user has to make use of the relationships between the individual data fields to browse them. The design is based on typical homepages on the Internet, using buttons to establish the links to related data fields.

Through this arrangement, it should be possible to gather and access all geological, paleoenvironmental, and paleontological data that are essential for the evaluation of the events at the D-C boundary.

The Early Mesozoic History of the Punnichy Arch, Southeastern Saskatchewan

J.E. Christopher [1]

Christopher, J.E. (2000): The Early Mesozoic history of the Punnichy Arch, southeastern Saskatchewan; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

1. General Setting

The Punnichy Arch is located in southeastern Saskatchewan between latitudes 50° and 52°, where on the present topographic surface it supports the broad interfluve and Quill Lakes internal basin between the Qu'Appelle and Saskatchewan rivers. On the sub-Jurassic erosion surface (Figure 1), the main components are the yoked Watrous and Wynyard domes (west to east). The Punnichy Arch (Christopher, 1980) is delimited by north-south elements: to the west by the Saskatoon Low along longitude 106° and to the east by the Tabbernor lineament belt along longitude 103°. The northern flank overlooks the 150 m deep Humboldt Trough, a linear Prairie Evaporite salt dissolution collapse sink, extending southeasterly from the Saskatoon Low to the Insinger Trough in the Tabbernor belt. To the southwest, the southern limb slopes to the 40 m (msl) contour, and to the east the arch juxtaposes the westerly projecting Yorkton salient of the north-south Moosomin–Hudson Bay structural belt. Crestal elevations on the arch increase southeasterly from 20 m (msl) on the Watrous Dome, to 120 m (msl) on the Wynyard Dome and 140 m (msl) on the Yorkton salient.

An inspection of the residual magnetic field map of the Precambrian basement (after Miles *et al.*, 1997), shows an approximate congruence of magnetic patterns with the structural elements of the Mesozoic Punnichy Arch

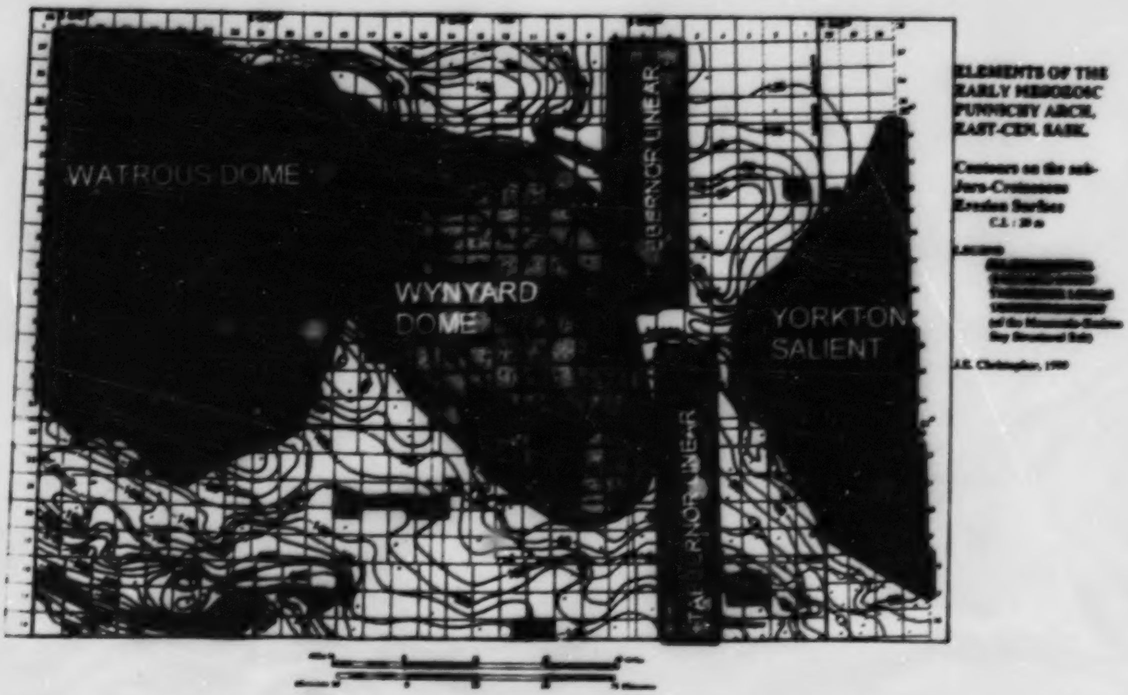
WATROUS DOME
WYNYARD DOME
TABBERNOR LINEAR
TABBERNOR LINEAR
YORKTON SALIENT
ELEMENTS OF THE EARLY MESOZOIC PUNNICHY ARCH, EAST-CEN. SASK.
Contours on the sub-Jura-Cretaceous Erosion Surface
C.I.: 20 m
of the Moosomin-Hudson Bay Structural Belt
J.E. Christopher

Figure 1 - Structural elements of the Early Mesozoic Punnichy Arch district, southeastern Saskatchewan showing the Watrous Dome, Wynyard Dome, Tabbernor lineament belt, and the Yorkton salient of the Moosomin–Hudson Bay structural trend. Contours on the subJura-Cretaceous erosion surface have a contour interval of 20 m.

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district. This indicates that the structural elements are genetically related to basement structure (Figure 2). The Watrous Dome, which is defined to the west by linears associated with the La Ronge Domain, conforms to a region of north-northwesterly aligned high- and medium-magnetic values that probably represent Glennie Domain mafic rocks. Northerly aligned medium to low values characterize the Wynyard Dome and the contiguous Tabbernor lineament belt, whereas similarly aligned high values to the east correspond to the Moosomin–Hudson Bay structural belt. Deep linear structural troughs on the erosion surface reflect salt dissolution sinks emanating from the Middle Devonian Prairie Evaporite. They also appear to relate to basement structure as their alignment is parallel with magnetic patterns, e.g. 1) the Jura-Cretaceous Insinger Trough (T28, T29, R7W2) and its extension to the south through Melville in the Tabbernor lineament belt, and 2) the Late Cretaceous–Cenozoic Last Mountain Lake sink (T22, R26W2) over a strong magnetic feature trending north-northwest in the Watrous Dome.

The sub-Cretaceous unconformity is made up of rocks ranging from the Precambrian basement and the Cambrian Deadwood Formation at Pinehouse and Wapawekka lakes in central Saskatchewan to the Oxfordian to Berriasian(?) Vanguard and Success strata at the border with the United States. It is a composite created by several cycles of uplift and denudation associated with the post-Mississippian–pre-Triassic Alleghanian and pre-Aptian Columbian orogenic pulses (Stott, 1984). The oldest of these unconformities dips south beneath the Jura-Triassic Watrous Formation into the Williston Basin. In the study area it is in contact with the Mississippian Madison Formation, the Upper Devonian Three Forks Group, and the Birdbear and Duperow formations. Southerly younging of easterly striking Paleozoic subcrops is a feature of this erosion cycle, and the subcrop pattern to the north is apparently of this age. A regional dip towards the Williston Basin during this hiatus is indicated. The later unconformities underlie the Jura-Cretaceous Success and the Lower Cretaceous Cantuar formations, respectively. Areally the larger of the two, the sub-Cantuar surface includes remnant bodies of a once extensive Success Formation on beds ranging from Late Jurassic in the south to Mississippian and Upper Devonian in central southern Saskatchewan (Maycock, 1967, Christopher, 1974, 1984a, and 1984b). In the Punnichy Arch district these bodies survive as discordant products of erosion and block faulting.

2. Watrous Dome

The striking discordance of outcrop trends in the Punnichy Arch district (Figure 3) reflects the three unconformities. Devonian and Mississippian carbonates strike northwest with relatively high relief from Manitoba to the Quill Lakes, where they turn abruptly southward under the Watrous Formation, before turning westward circumferentially around the

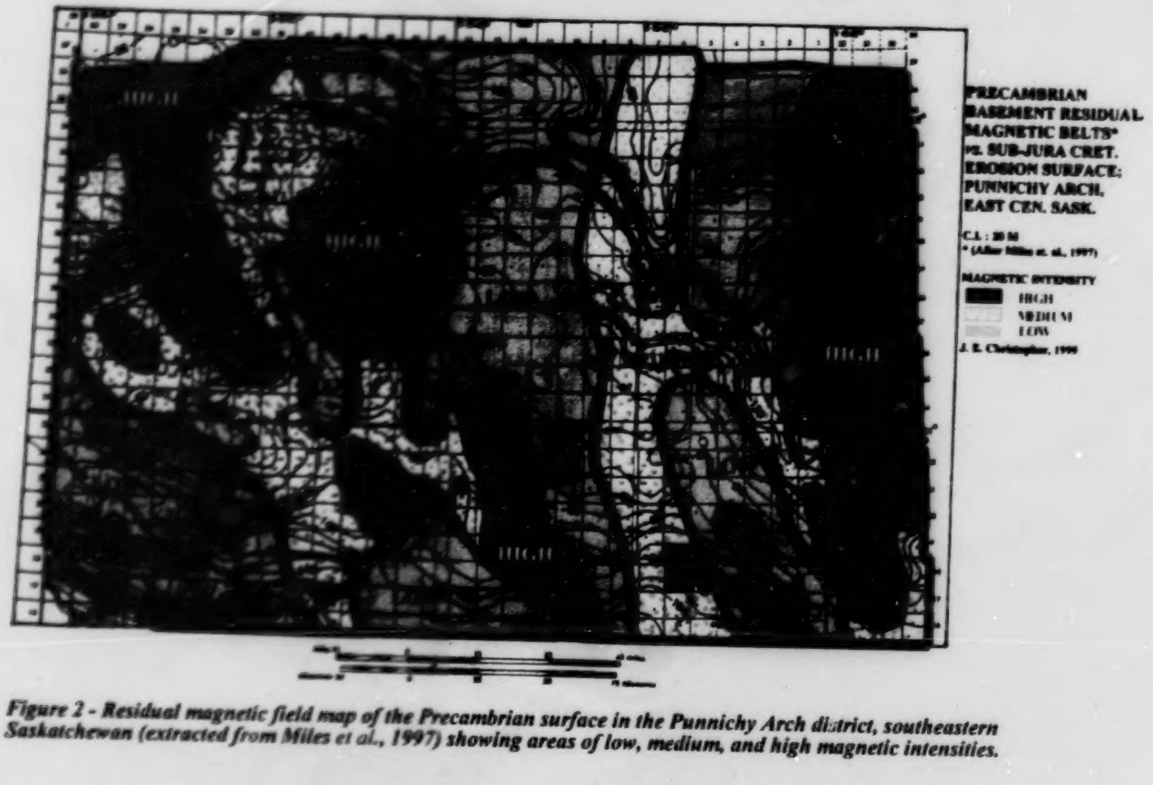

Figure 2 - Residual magnetic field map of the Precambrian surface in the Punnichy Arch district, southeastern Saskatchewan (extracted from Miles et al., 1997) showing areas of low, medium, and high magnetic intensities.

southern flank of the Watrous Dome, and finally north and westward 10 km west of longitude 106°. On the dome, the subcrop pattern is annular and stripped back in a fashion typical of that on a southerly plunging anticlinal structure. The Watrous Formation is broadly exposed west of the Quill Lakes and its eastern edge reaches north to T36 and northwest to T44 where it turns circumferentially south just east of longitude 106°, to cross the northwesterly trace of the Madison subcrop on the western flank of the Watrous Dome. Thus, as defined by the annulus of Watrous subcrop in the north and the Madison subcrop in the south, the Watrous Dome encompasses an area of 22 500 km^2. Like the Madison, the Torquay and Birdbear subcrops sweep in southward-bending arcs, but triple in areal extent across the dome because of flattened dips. Both thickness of the Watrous Formation in this region, which ranges up to 75 m, and its stratigraphy of calcareous, red, argillaceous, quartzose sandstone, noncalcareous mudstone and anhydrite deviate little from that in the PCS Lanigan 3-28-33-23W2 core described in the Appendix. Karsting of the subjacent carbonates exists, as indicated by the 17 m of brecciated dolomite at top of the Duperow Formation.

The northerly aligned eastern Watrous subcrop strikes southeasterly beneath the Middle Jurassic Gravelbourg and Shaunavon formations to the Manitoba boundary. Little evidence exists of a more northerly extent of the Watrous Formation in this region, and from this edge it thickens southward into the Williston Basin. Thus during the Jura-Triassic, the Watrous Dome was a depositional arm of the Williston Basin, and to the east the Wynyard Dome–Yorkton salient presented a significant upland barrier to the Jura-Triassic marine transgression.

The combined subcrop of the Shaunavon and Gravelbourg formations ranges from 5 to 50 km in width, but is generally 30 to 40 km. Their combined thickness generally is between 76 and 85 m. The exposure belt blankets the southern slope of the Punnichy Arch; thus it trends northwesterly, but sweeps out a narrow southerly arc in the Tabbernor belt at Melville, in conformity with the overlying Rierdon Formation to the south. Most of the exposure represents a back-stripping of Rierdon shale from the Shaunavon-Gravelbourg cuesta of resistant, cemented limestone, dolostone, and sandstone. To the west, across the southern part of the Watrous topographic basin, the subcrop turns gently southwesterly along an irregular front. However, Shaunavon-Gravelbourg marine limestone outliers capping Watrous strata to the north, as at the PCS Lanigan 3-28-33-23W2 site, indicate a deep northerly penetration of the Watrous basin. In view of the Middle Jurassic overlap of the Watrous, this advance extended well beyond the Watrous edge at T44.

3. Wynyard Dome

On the Late Paleozoic subcrops of the Wynyard Dome and in the area to the east, vestiges of the Middle Jurassic transgression of the Wynyard Dome are absent or not recognized (perhaps because of a facies change

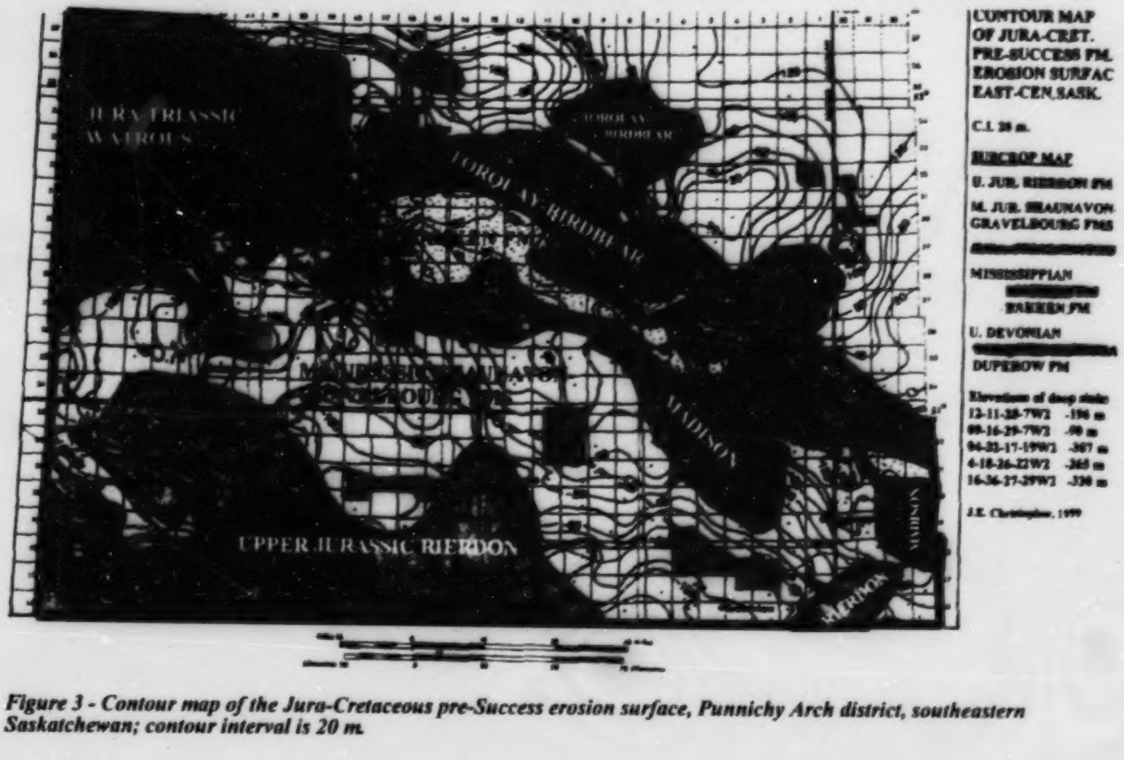

Figure 3 - Contour map of the Jura-Cretaceous pre-Success erosion surface, Punnichy Arch district, southeastern Saskatchewan; contour interval is 20 m.

from marine to nonfossiliferous continental). Moreover, the overlap of the Watrous Formation on the relatively steep flank of the dome indicates proximity of a shoreline, the sediments of which are abundantly in evidence to the east along longitude 102° southward from T22 (Kreis, 1991). Thus erosional backstripping of Middle Jurassic strata off the Wynyard Dome is implied.

The Madison limestone is the predominant ridge-former on the pre-Cantuar erosion surface. Along the Punnichy Arch east of the Quill Lakes, the subcrop width is 10 to 24 km. The formation is dissected lengthwise along the crest of the arch in the manner of a breached anticline, as indicated by Mississippian Bakken, and Devonian Big Valley and Torquay inliers. Rising 40 to 50 m above the inner valley, the Madison ridge to the north is 3 to 5 km wide and 120 km long. The valley floor is 10 to 20 km wide, and heads in the southeast against the Madison limestone escarpment between Yorkton and Melville. There, at the entry to the Broadview structural depression, the Madison exposure widens to 64 km over the Tabbernor lineament belt, and the valley steps up to an amphitheatre controlled by the re-entrant in the Middle Jurassic escarpment west of Esterhazy. At the northwestern end, on the flattened top of the Wynyard Dome, the valley broadens into a 56 km wide, circular, Bakken sandstone-floored flat. To the immediate west of this flat, the Mississippian escarpment becomes sub-Watrous as it turns south along the Watrous Dome. Middle Jurassic onlap of the southern flank of the Wynyard Dome was apparently preceded by progressive northward planation of the Madison Formation from an original thickness of about 60 m to less than 25 m. Thus the axial valley on the Madison escarpment was probably initiated in the Middle Jurassic as a backshore flanking basin, and was subsequently deepened and flushed of sediments by later Jurassic erosional events.

The Torquay Formation outcrop width of 15 km is considerably out of proportion to its thickness of 65 to 70 m, a reflection of the readily eroded quality of its dissolution-brecciated carbonates and clastics. In contrast, the Birdbear Formation of similar thickness, but a well indurated carbonate, presents only a narrow exposure width of some 5 km. Both strike northeasterly on the northern flank of the Punnichy Arch east of the Watrous Dome; however, if the outliers of these formations to the north of this subcrop are included, the width of the combined exposure belt exceeds 60 km. Thus the erosional surface cuts across the 140 m thick strata on a 2.3 m/km slope to the north; i.e. the post-Triassic terrain would have been nearly flat. If the 75 m thickness of the Watrous Formation to the west indicates infill of the Watrous topographic basin, then the Wynyard Dome would have been at least that high above the Watrous Dome as taken on the sub-Triassic erosion surface. Capping Middle Jurassic sediments in the Watrous basin may then have onlapped the dissected Madison Formation from the west.

The Wynyard Dome as defined to the north by the Torquay-Birdbear outliers, and to the south by the Middle Jurassic subcrop, is the main area of occurrence of the "Insinger beds", the Punnichy Arch homologue of the Success Formation (Figure 4). At the reference well, Sohio W.P. Insinger 9-16-29-7W2 (Price, 1963; Christopher, 1980, 1987), this formation comprises three units: A, B, and C (oldest to youngest), each terminated by coal beds. Quartz, ranging from very fine- to coarse-grained sand, grit, and conglomerate, is dominant, with subordinate grain-aggregate and cement of chert and chalcedony, black shale, and reddish brown dolostone. Calcareous cement has a minor presence in Unit C, but a white siliceous kaolinitic matrix is pervasive in all units. Unit A fines upward from coarse-grained sandstone and grit, interbedded with subordinate poorly sorted fine- and medium-grained sandstones, into fine-grained, pyrite-cemented sandstone beneath the cap of carbonaceous and coaly beds. Abundant lithic grains in the lower part of the unit reflect Bakken and Upper Devonian rock sources. White fragments of Madison chert, both porcelaneous and chalcedonic, dominate the lower two-thirds (27 m) of Unit B. The upper third of the unit features the more typical fine- to medium-grained, kaolinite-indurated, sphaerosideritic, quartzose sandstone with subordinate beds of black coaly shale. Coal is present in the upper 6 m. Unit C cuttings indicate a uniform suite of white kaolinite- and silica-cemented, fine-grained sandstone with some calcareous and marly interbeds, as well as brown siderite- and brassy pyrite-cemented beds. A capping coal under a red-oxidized shale marks the contact with the Cantuar Formation.

Success sedimentation apparently occurred in an aggradational environments of river channel, over-bank and finally, lacustrine swamp that infilled an episodically subsiding basin. The obvious source of chert was the local Mississippian limestone, which formed a topographic back-drop to the Insinger and outlying lowlands. The quartzose feldspathic sandstone influx was likely sourced from the Precambrian Shield to the north and east. By the latter half of Unit B time, the Wynyard Dome, which had been down-tilted eastward by subsidence in the Tabbernor lineament belt against uplift of the Precambrian Superior Province, was buried by these sediments to an eventual depth of 122 m. As indicated by the Success onlap, the crown of the Watrous Dome became the highest region on the Punnichy Arch.

4. Tabbernor Lineament Belt

Not much of the Success strata would have survived the succeeding pre-Cantuar erosion period but for the drastic modification of the Success terrain by site-specific collapse of the underlying Devonian carbonates into caverns created by the dissolution and removal of the Devonian salt beds. The northern front of the Punnichy Arch shares in the irregularities of the Success basin, and the Insinger Trough, in R7W2, T27 to T29 inclusive, is an archetypal compound salt dissolution sink. Located over the Cussed Creek

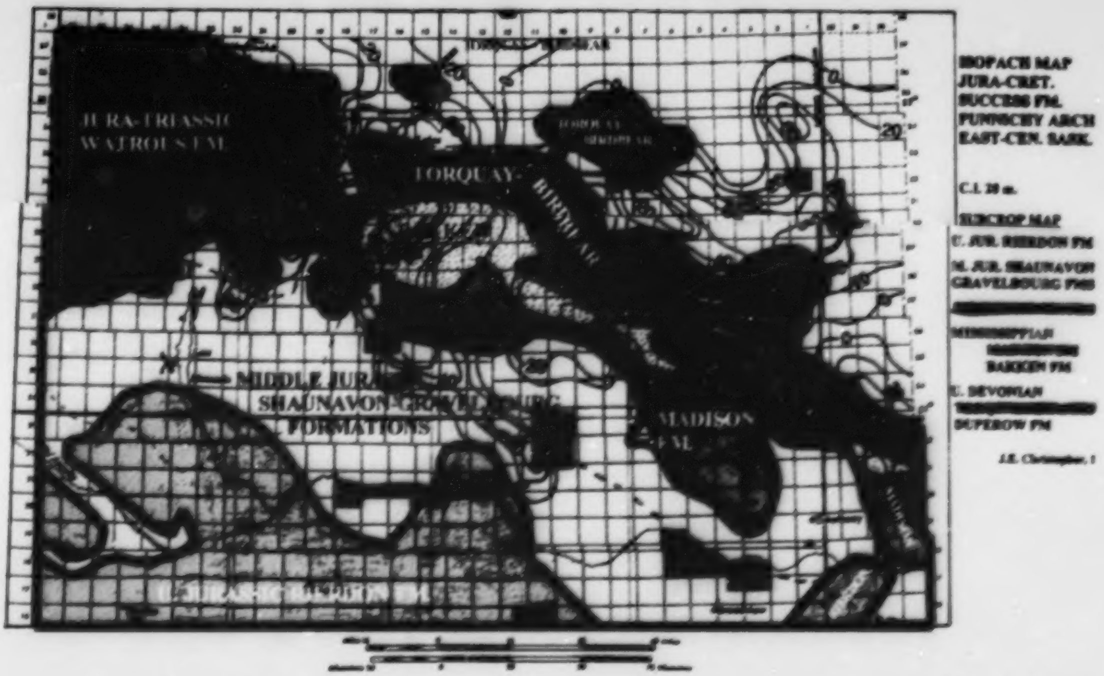

Figure 4 - Isopach map of the Jura-Cretaceous Success Formation, Punnichy Arch district, southeastern Saskatchewan.

embayment in the Prairie Evaporite salt beds (Li *et al.*, 1998), the Success and Cantuar strata in the trough, as shown in Figure 5, have undergone large-scale displacements and truncations.

The line of section (Figure 5) is aligned south from the Sohio Western Petroleum Insinger NE-16-29-7W2 well to Winsal Jedburgh 12-11-27-7W2, a distance of 15 km. The stratigraphic datum is at the top of the marine Albian Pense Formation. The three major unconformities depicted are at the base of the Pense, the Aptian-Albian Cantuar, and the Jura-Cretaceous Success formations. The Success section at the Insinger well is downset 122 m with respect to the section at the neighbouring Sohio Theodore 4-22-28-7W2 well, as indicated by their common stratigraphic base on the Upper Devonian Torquay Formation. This Theodore well is taken as a benchmark because it shares the same sub-Success stratigraphic base on the Torquay Formation with that at B.A. Husky Springside 8-29-27-7W2 located at the end of the trough. Just beyond, at Winsal Jedburgh 12-11, the Success Formation rises onto the Mississippian Madison limestone. Accordingly, the Success sections at Theodore 16-9-28-7W2 and 12-11-28-7W2 are also downset. However, the sub-Success erosion surface at these sites lies within 10 m of the Souris River contact, and some 229 m of Upper Devonian strata involving the Duperow, Birdbear, and Torquay formations are missing from the sections. Insertion of this stratal thickness below the sub-Success erosion at Theodore 12-11 would raise the erosion surface to the stratigraphic horizon of the sub-Pense unconformity. Although the combined thickness of the Success Formation (110 m) and the Cantuar Formation (121 m) approximates the thickness of the missing Devonian strata, the loss of the latter does not equate to simple erosional cut. The Success Formation is present in its entirety in all of the wells, from Springside 8-29 in the south where it onlaps the Torquay Formation to Theodore 4-22 and Insinger NE-16 in the north, where it also overlies the Torquay Formation. Thus it is likely that the pre-Success erosion surface at Theodore 12-11 and 16-9 lay above the sub-Pense unconformity, on an uplifted block that was eroded to within 10 to 17 m of the Souris River contact. This contact at Theodore 12-11 shows a sub-Pense stratigraphic relief of 52 m above that at Springside 8-29. Episodic settling of the uplifted block accompanied Success and Cantuar infill to depths of 110 m and 121 m respectively. The pre-Pense stratigraphic relief on the Souris River Formation with respect to the Springside 8-29 site indicates a 52 m erosional loss of the Cantuar to pre-Pense truncation (Figure 5).

The present -205 m (msl) structural elevation of the Souris River Formation at Winsal Theodore 12-11 versus the -150 m (msl) at Chel TRC Tech Theodore 16-9 indicates a relative post-Mannville lowering of the former site by 55 m. A measurement of subsidence at the Sohio Western Petroleum Insinger NE-16-29-7W2 site, where the movement was apparently unidirectional, is obtained by adding the Cantuar thickness of 70 m to the 122 m of Success strata, for a total of 192 m. This value is similar to the pre-Pense net subsidence of 177 m at the Winsal Theodore 12-11

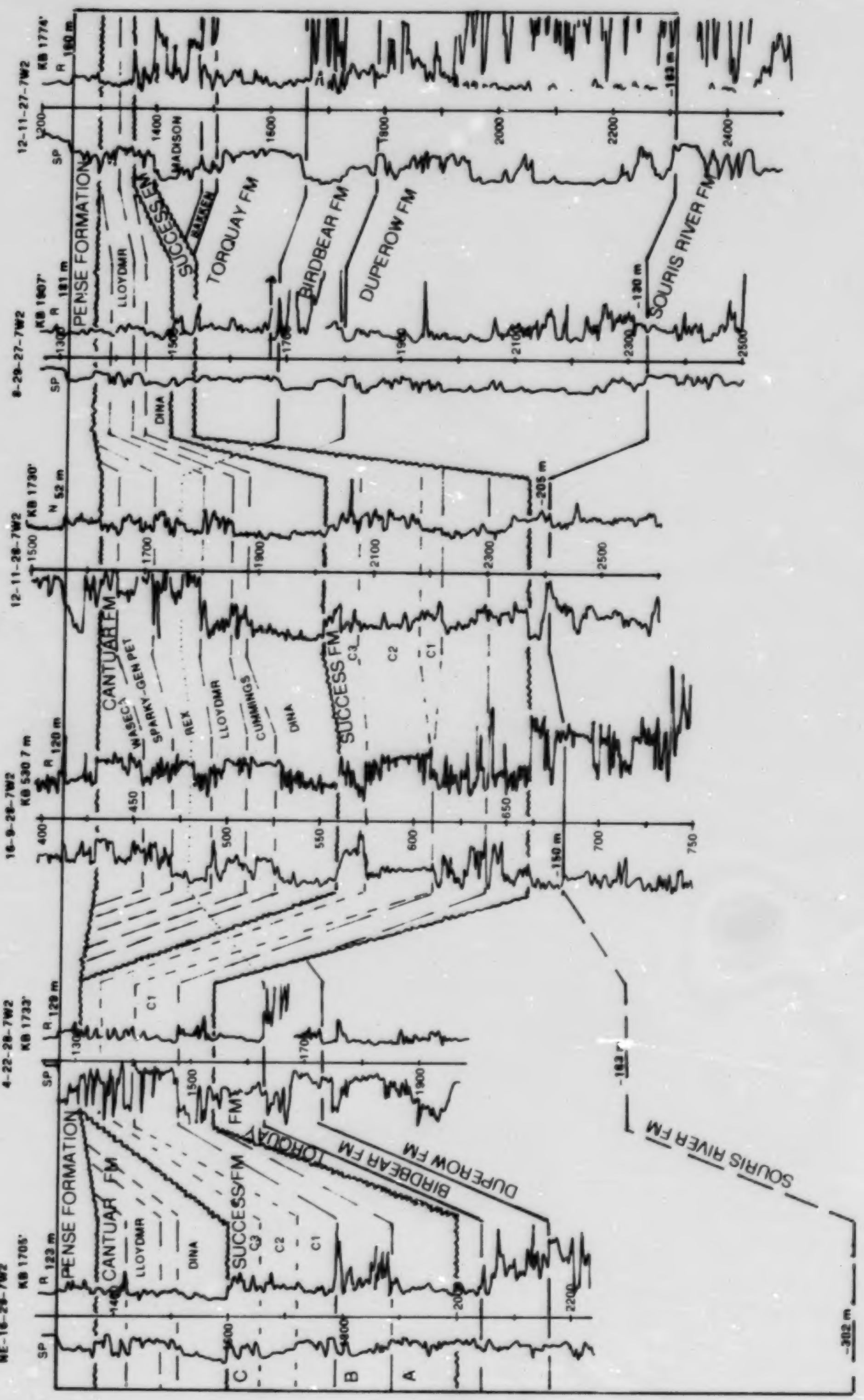

Figure 5 - North-south stratigraphic cross-section from Sohio Western Petroleum Insinger NE-16-29-7W2 to Winsal Jedburgh 12-11-27-7W2, Punnichy Arch district, southeastern Saskatchewan.

well. The elevation of the projected Souris River contact in the Insinger well at -301 m (msl) is the lowest in the line of section, and probably reflects complete dissolution of the Prairie Evaporite. At the Theodore 16-9 well, this contact at -150 m (msl) is above 150 m of remaining Prairie Evaporite salt beds, which if removed, would lower the Souris River contact to -300 m, i.e. the same elevation as at the Insinger well.

Elevation on the Pense stratigraphic datum at the Insinger NE-16, Theodore 4-22, and Theodore 16-9 localities ranges between 123 m and 120 m, but descends to 52 m at Theodore 12-11 where the Pense datum is 129 m below its neighbor to the south at Springside 8-29. Thus early Albian collapse at the Insinger site is succeeded by post-Pense collapse at Theodore 12-11. Apparently the wells to the north also show the latter movement, but only by half as much. With respect to the Theodore 12-11, the 129 m downset may reflect loss of Prairie Evaporite salt beds from the section, and compared with the 150 m salt section at Theodore 16-9, only 21 m of salt beds have survived. It is noteworthy that the pre-Pense Theodore 4-22 section displays a stratigraphic uplift similar to that postulated for the 16-9 and 12-11 sites, but it is a 70 to 122 m thick Cantuar section which has been removed. Both structural and stratigraphic relief on the Souris River and the B bed of the Success Formation with respect to the Insinger section are similar; i.e. 137 m and 122 m respectively. These differences indicate a thickness of about 130 m of Prairie Evaporite salt beds is present at the Theodore 4-22 site. Because the Theodore 16-9 site also retains a similar thickness of Prairie Evaporite salt, pre-Pense uplift and erosion of the Devonian strata are indicated at the Theodore 16-9 and 12-11 sites to be a function of tectonic forces. These two wells are located about 1.5 km apart (east-west) on a structure astride the Insinger Trough, which is located over a seismically detected basement graben in the Tabbernor lineament belt (Li *et al.*, 1998, p180).

5. The Arch in the Early Cretaceous

As shown in Figure 5, the Success stratigraphic base rises southward onto the Mississippian limestone escarpment, whereon Success sediments infill several valley re-entrants. The regional net effect of this aggradation was a pediment modified by low rises and depressions. This pediment underwent abrupt uplift onto the Swift Current Platform in southwestern Saskatchewan and the Precambrian Shield to the east and northeast, but moderate subsidence and eastward tilt on the Punnichy Arch toward the Tabbernor belt. The movements reversed the Jurassic southerly regional gradients on the Williston Basin to those directed north and northwest to the Cold Lake–McMurray Basin in east-central Alberta (Christopher, 1980, 1984b, 1997; Poulton, *et al.*, 1994; Hayes *et al.*, 1994). The drainage system detailing the pre-Cantuar erosion surface in part re-occupied Success ancestral valleys as valley-in-valley systems, and in part stripped away Success sediments (Figure 6). Initial Cantuar deposition proceeded by cut-and-fill in a drainage

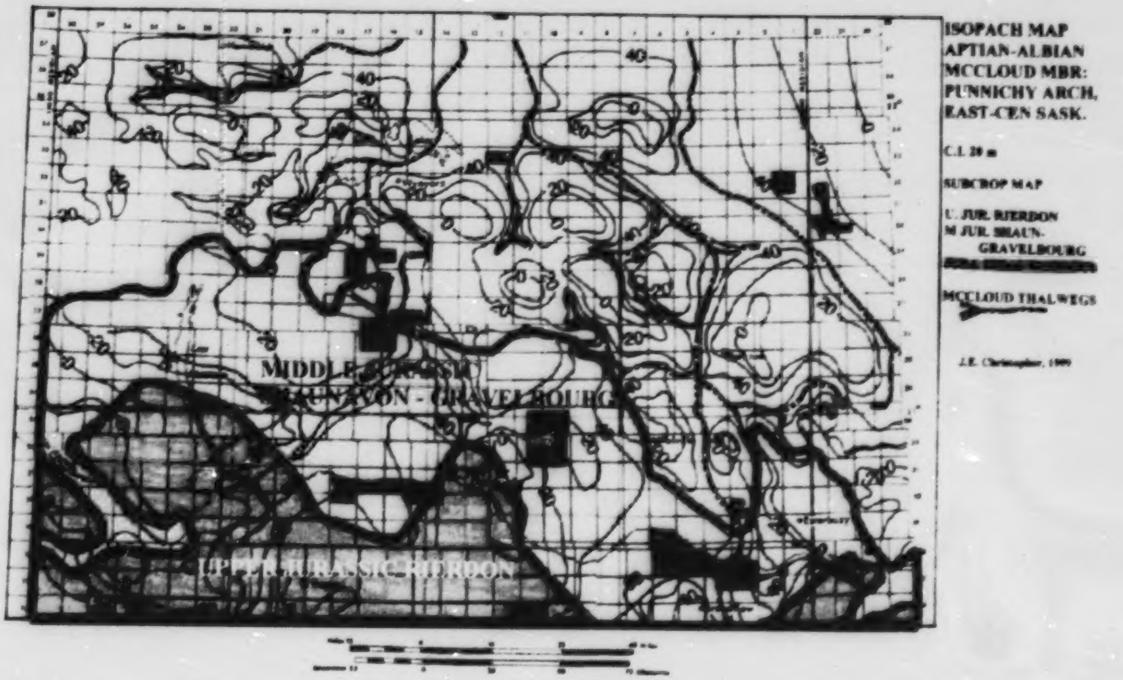

Figure 6 - Isopach map of the Aptian-Albian McCloud Member (Dina-Cummings) of the Punnichy Arch district, southeastern Saskatchewan.

system pursuing a northerly course along the Moosomin–Hudson Bay structural front and the Tabbernor lineament belt, collecting tributary-supplied quartzose sands from the Precambrian Shield. Aggradation in the channels was accelerated by an oscillating marine transgression from the northwest. By Lloydminster times, the Punnichy Arch was blanketed. As indicated in the core description from PCS Lanigan 3-28-33-23W2 (see Appendix), the Cantuar section is abbreviated by sub-Pense erosion.

The Dina sandstones of the Mannville Group, which, with the overlying argillaceous Cummings beds, form the McCloud Member of the Cantuar Formation, more or less delineate the underlying topography. The Chaplin Lake (in the west) and Assiniboia (in the east) trunk paleovalleys cross the Punnichy Arch between the Watrous and Wynyard domes and along the Tabbernor lineament belt. A grid of tributary valleys controlled by underlying cuestas feeds into the Assiniboia north of the arch. As typified in the core of the Mannville section at PCS Lanigan 3-28-23-23W2, the Dina sandstones are quartzose, low in matrix clay, and built up as upward-fining cyclic beds. They grade per cycle and overall, from coarse to medium grained in the lower part of the member and medium to fine grained in the upper, and from medium-scale trough and planar cross-bedded to finely current-bedded. The cyclic sequences are interrupted by diastemic breaks with weathering horizons, cemented and erosional surfaces. Topward in the member, grey-black shale laminae occur, commonly enclosing sandy bioturbation pods. Coarser textured beds are found in the thalwegs and finer beds tend to be more widespread on the upper topographic flats. The older beds are generally fluviatile, and the younger, fluviatile deposits reworked in an estuarine setting reflective of marine incursions. The Cummings shale is generally marine. Thickness of the McCloud Member ranges up to 45 m.

The Cantuar Formation thickens to 165 m to the north and to 100 m to the south of the Punnichy Arch. The erratic thickness on the arch, as indicated in Figure 5, reflects 1) truncation under the sub-Pense unconformity and 2) site preservation in salt dissolution sinks as proposed for the Success Formation. The former is a result of planation by the widespread marine transgression that accompanied rapid foundering of the Swift Current Platform. The regional pattern of pre-Pense stripping of the Punnichy Arch is illustrated by the distribution of subcrops, whereby strata as old as the Mississippian Bakken and as young as the Waseca Member of the Cantuar Formation display annular patterns of outward younging surrounding highs on the arch as well as the arch itself (Christopher, 1984a).

The type section of the Pense Formation (Price, 1963) is located at the Sohio Cdn Dev Pense 14-6-17-22W2 on the southern flank of the Punnichy Arch. The formation here comprises four units (youngest to oldest) as follows:

Sohio Cdn Dev Pense 14-6-17-22W2
K.B. 581.9 m (1909 ft)
Depth (m)

Unit 4 (5.5 m)

808.0 - 813.5 Shale: dark grey, abundant fish bones and glauconite; grades through interbedded, quartzose siltstone and shale into burrowed very fine-grained, quartzose sandstone.

Unit 3 (4.1 m)

813.5 - 817.6 Shale: dark grey, grades into bioturbated siltstone.

Unit 2 (8.1 m)

817.6 - 818.2 Siltstone: quartzose, argillaceous, chloritic; coarsens upward into shale-laminated, burrowed, fine-grained, quartzose sandstone with accessory green chlorite, green glauconite and white kaolinite.

818.2 - 825.7 Siltstone: quartzose; interbeds of fine-grained, sideritic, quartzose sandstone and gritstone of rounded black and grey chert; fines upward into shaly siltstone with shale-draped ripple cross-beds and abundant carbonized vegetal matter.

Unit 1 (16.2 m)

825.7 - 829.1 Sandstone: quartzose, light grey, very fine- and fine-grained, kaolinitic matrix, friable; accessory kaolinite after feldspar, spheroidal chlorite, and grey chert.

829.1 - 841.9 Shale: dark grey, bioturbated near the base and the top; minor thin, medium grey siltstone and very fine-grained, quartzose sandstone partings and thin interbeds.

The Pense units are regional throughout the Punnichy Arch district and contain a conspicuous friable, quartzose sandstone component. They thereby form a porous base to the massive aquiclude of overlying Joli Fou black shale, which otherwise by virtue of the unconformity might have served as an effective trap for potential up-dip migrating oil in the Cantuar Formation.

6. Petroleum Prospects

The known petroleum source beds are located in Paleozoic strata rather than Mesozoic. South of latitude 51°, up to 320 m of Jurassic clastics and carbonates separate the Mannville from potential Mississippian source beds. Thus the presence of regional intersecting lineaments and potentiometric cells for upward migration of formation water is as important a prerequisite for oil accumulation in the Mannville as the presence of suitable reservoirs. This combination of geological elements is present at the Mannville Wapella and the Middle Jurassic Moosomin and Red Jacket oilfields along the Moosomin–Hudson Bay structural belt immediately to the south of the study area (Kreis, 1991). Reiteration of the Wapella play in the Punnichy district is dependent on the discovery of other northeasterly trending Mannville and Jurassic channel sandstones in updip re-entrants of the structural front. A pyrobitumen show in the Cummings Member displayed in the core from Imperial TW Broadview 14-17-15-4W2 indicates the passage of hydrocarbons in the Tabbernor lineament belt, as does an oil show farther west on the Punnichy Arch in the Gravelbourg Formation at TW Ituna 1-29-25-12W2. The latter occurs at the edge of the formation on a knob at the head of a southwesterly plunging trough.

Of those formations on the south limb of the Punnichy Arch between the Madison and the Colorado shales, the Shaunavon, Gravelbourg, Success, and Mannville strata are available as hydrocarbon reservoir rock, especially on the Wynyard Dome (Figure 1). The dome is flanked to the west and east by Late Cretaceous sinks which may have served as conduits for hydrocarbons migrating from Paleozoic source beds. Reservoirs would tend to be located on the Jurassic capped mesas and in Dina and Lloydminster channel and bar sandstones encapsulated in mudstone. The Madison limestone at the crest of the Punnichy Arch forms a north-facing escarpment overlooking varied Success valley fills that include poorly permeable cherty pavements. The potential for oil reservoirs is enhanced where permeable basal Success sandstones underlie the silicified beds. The Mannville facies are similar to those on the Unity Terrace of the Lloydminster heavy oil district in that they include a more-or-less systematic distribution of shore, shoal, and channel sandstones. Also the post-Pense subsidence in the Humboldt Trough, like the North Battleford Trough, presents an up-dip impediment to northward migration of oil. Scattered oil shows across central Saskatchewan, reported by Simpson (1970) in the Upper and Middle Devonian at Western Petroleum 12-23-29-32W1, Northern Royalties 6-35-29-32W1, Trail Blazer 1-31-44-2W2, and Husky Phillips Fitzmaurice 16-18-27-8W2, raise the prospecting potential of these strata as an alternate and extant oil source for Mannville reservoirs. Three of these shows are spatially associated with the Moosomin–Hudson Bay structural belt, and the Tabbernor lineament belt. Enhanced thermal maturity in the Ordovician of the Tabbernor belt from the Nesson Anticline to the Punnichy Arch as mapped by Osadetz *et al.* (1989) predicted and impelled the northward spread of discoveries in the Lower Paleozoic to the Qu'Appelle River. Moreover, a Late Paleozoic geothermal event proposed by Li *et al.*, (1998) has also been invoked to account for these shows.

7. Acknowledgments

Permission by the Potash Corporation of Saskatchewan to publish the description of the section from PCS Lanigan 3-28-33-23W2 is gratefully acknowledged. The author thanks C.F. Gilboy, F. Haidl, and C. Harper for critical review and editing, and E. Nickel and P. Weir for digital input of the figures.

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Appendix – Core Descriptions

PCS Lanigan 3-28-33-23W2 **K.B. 538.1 m (1765.6 ft)**

Depth in feet (m)

PENSE FORMATION

1436.0 - 1438.0 (437.7 - 438.3) Mudstone: dark grey; subordinate light grey, fine-grained, quartzose sand as component and thin lenticles; grades into

1438.0 - 1443.5 (438.3 - 440.0) Sandstone: quartzose, fine grained, argillaceous, mottled light and dark grey, calcareous, moderate to well indurated, earthy, bioturbated (mostly feeding burrows, 1 to 4 mm diameter); sharp contact.

1443.5 - 1453.0 (440.0 - 442.9) Sandstone: quartzose, fine grained, light grey; dark grey, argillaceous very fine-grained sandstone below massive upper 0.05 m; abundant feeding burrows in the argillaceous beds; shale blackens downward, and below 1446 ft (440.7 m) sandstone features thin ripple laminae with shale drape; interbedded with decimetre-thick black shale below 1450 ft (442.0 m); sharp, irregular contact under basal black shale.

1453.0 - 1453.5 (442.9 - 443.0) Sandstone: quartzose, very fine grained, dense, iron cemented, rusty brown, current bedded; sharp, basal contact.

1453.5 - 1457.8 (443.0 - 444.3) Shale: black, minor ripple and current-bedded laminae and laminae groups of light grey, very fine-grained, quartzose sandstone; abundant feeding burrows; sharp, irregular contact.

1457.8 - 1458.3 (444.3 - 444.5) Sandstone: as at 1453.0 ft (442.9 m).

1458.3 - 1463.5 (444.5 - 446.1) Shale: as at 1453.5 ft (443.0 m); no bioturbation pods; sharp basal contact.

1463.5 - 1469.0 (446.1 - 447.8) Siltstone: quartzose, argillaceous, medium grey; grades into black shaly mudstone laminated with subordinate current-bedded siltstone; below 1468 ft (447.4 m) siltstone is dense, argillaceous with trace of current bedding; sharp contact marked with pyritic nodules.

CANTUAR FORMATION

Sparky Member

1469.0 - 1470.0 (447.8 - 448.1) Sandstone: quartzose, fine grained, subordinate coarse grained, medium grey speckled with red brown siderite, silica cemented, irregularly bedded.

1470.0 - 1471.5 (448.1 - 448.5) Mudstone: massive, medium grey; subordinate coarse-grained, rusty brown sphaerosiderite increasing to 40% downward.

1471.5 - 1472.8 (448.5 - 448.9) Claystone: platy, dark grey, sharp, irregular contact.

1472.8 - 1476.0 (448.9 - 449.9) Sandstone: quartzose, very fine grained, medium grey, abundant muscovite; downward increasing dark grey shale laminae; strongly contorted decreasing downward to nearly flat bedded; sharp, irregular basal contact.

1476.0 - 1479.5 (449.9 - 451.0) Sandstone: quartzose, very fine grained, well sorted, friable, abundant muscovite; about 7% sphaerosiderite over upper half; scattered concretionary nodular pyrite; sharp basal contact.

1479.5 - 1480.3 (451.0 - 451.2) Sandstone: quartzose, very fine grained, light grey speckled with brown, well sorted, silica cemented, dense; about 20% coarse-grained sphaerosiderite; low-angle cross bedded to flat current bedded; sharp, irregular basal contact.

General Petroleums Member

1480.3 - 1486.0 (451.2 - 452.9) Claystone: waxy, dark grey mottled with red and yellow flaky plant coatings over upper half; scattered carbonized filaments below.

1486.0 - 1487.7 (452.9 - 453.5) Mudstone: massive, medium grey, moderately well indurated, scattered red brown iron mottling downward.

1487.7 - 1499.5 (453.5 - 457.0) Sandstone: quartzose, very fine grained; subordinate coarse-grained, brown sphaerosiderite; very argillaceous, well indurated, medium grey mottled and speckled with iron stains; sharp(?) contact.

Rex Member

1499.5 - 1512.5 (457.0 - 461.0) Mudstone: subordinate very fine-grained quartzose sand, medium grey, massive; sandier and severely contorted over lower 0.3 m, and pebbly ironstone conglomeratic with carbonized woody fragments near base; bottom of section on slickensided shear dipping about 25°.

1512.5 - 1516.0 (461.0 - 462.1) Mudstone: clayey, dark grey to medium grey downward, blocky to platy.

1516.0 - 1519.5 (462.1 - 463.1) Siltstone: quartzose, argillaceous, medium grey, massive, hard; sharp, irregular contact.

1519.5 - 1521.5 (463.1 - 463.8) Sandstone: quartzose, fine-grained, light grey, annealed breccia; subordinate coarse-grained brown sphaerosiderite; calcite cemented over upper 0.3 m, well indurated below; grades into

1521.5 - 1527.5 (463.8 - 465.6) Mudstone: light green-grey to medium grey downward; faintly flasered with sandy laminae; abundant small burrows over basal 0.05 m; sharp, irregular contact.

1527.5 - 1529.5 (465.6 - 466.2) Siltstone: argillaceous, light green-grey, massive; abundant siderite infilled vertical burrows; sharp, irregular contact.

Lloydminster Member

1529.5 - 1531.0 (466.2 - 466.6) Mudstone: platy, argillaceous, light green-grey, platy, hard, shaly and clayey over lower half; abundant ironstone nodules and silty lenticles; sharp contact.

1531.0 - 1536.0 (466.6 - 468.2) Mudstone: dark green-grey, abundant carbonaceous flecks and sulphurous coaly fragments and lenticles; sharp, irregular contact.

1536.0 - 1539.5 (468.2 - 469.2) Sandstone: quartzose, fine grained, grey-white, kaolinitic, moderately indurated, earthy in part; blocky structure with scattered coaly fragments and irregular pyritic masses at the top; about 15% black shale ripple laminae below.

1539.5 - 1541.0 (469.2 - 469.7) Sandstone: quartzose, fine grained, light grey, current bedded, well sorted, densely calcite cemented; scattered black shale ripple laminae toward base.

1541.0 - 1543.5 (469.7 - 470.5) Sandstone: quartzose, very fine grained, grey-white, kaolinitic, massive, blocky structure, moderately indurated, bioturbated towards base.

1543.5 - 1544.0 (470.5 - 470.6) Shale: black, subordinate graded laminae of white, very fine-grained, quartzose sandstone and bedding-aligned bioturbation pods; rare *Chondrites*; well indurated; sharp, irregular contact on oxidized, vertically burrowed hardground of cemented sandstone.

1544.0 - 1546.0 (470.6 - 471.2) Sandstone: quartzose, fine grained, kaolinitic, grey-white, moderately indurated, about 15% coarse-grained, reddish brown sphaerosiderite at 0.03 m; flow distorted bed and lenticular layering below with slight increase in dark grey argillaceous content; strongly bioturbated with *Teichichnus* conspicuous near base.

1546.0 - 1548.7 (471.2 - 472.0) Sandstone: quartzose, fine grained, kaolinitic, grey-white, cross bedded; thinly interbedded with ripple laminae of black shale; about 7% coarse-grained sphaerosiderite; grades into black shale over basal 0.25 m; sharp, irregular contact with coaly fragments on oxidized surface.

Cummings Member

1548.7 - 1553.5 (472.0 - 473.5) Mudstone: medium green-grey, platy; interbedded with subordinate sandstone: quartzose, very fine grained, kaolinitic, grey-white and laminated with light grey-green shale; strongly contorted, scattered brown sideritic nodules; sharp, irregular contact lined with sideritic nodules and pyrite crystals.

Dina Member

1553.5 - 1556.2 (473.5 - 474.3) Sandstone: quartzose, fine grained, abundant muscovite, light grey, well sorted, friable, permeable; flat bedded with trace of fine current beds; sharp contact.

1556.2 - 1556.5 (474.3 - 474.4) Siltstone: quartzose, subordinate grey-black muscovitic shale; ironstone cemented in part; sharp contact.

1556.5 - 1567.5 (474.4 - 477.8) Sandstone: as at 1553.5 ft (473.5 m); ripple drift bedded increasing to 20° avalanche slopes over lower half; sharp contact on oxidized red and green laminated shale, 0.02 m thick.

1567.5 - 1580.5 (477.8 - 481.7) Sandstone: quartzose, fine grained to medium, well sorted, subangular with overgrowths; scattered red jasper, white kaolinite; abundant muscovite; medium grey, massive, with intervals marked by steep, planar cross beds; basal contact on wavy, oxidized red and green mudstone, 0.01 m thick.

1580.5 - 1641.0 (481.7 - 500.2) Sandstone: as at 1567.5 ft (477.8 m), but dominantly medium grained; interbedded with high-angle decreasing downward to low-angle planar cross-beds; below 1635 ft (498.3 m) decimetre-thick interbeds laminated with subordinate coarse-grained sphaeropyrites; sharp, irregular, pyrite-encrusted contact.

SUCCESS FORMATION

1641.0 - 1646.0 (500.2 - 501.7) Coal: black, fusain-rich, argillaceous, sulphurous.

1646.0 - 1647.0 (501.7 - 502.0) Sandstone: quartzose, fine grained, coaly, argillaceous, black, friable, massive downward; sharp contact.

1647.0 - 1648.0 (502.0 - 502.3) Claystone: kaolinitic; tan, massive; abundant carbonized criss-crossed reeds; sharp(?) contact on dark brown, pyrobituminous layer. Basal contact on the Shaunavon Formation.

SHAUNAVON FORMATION

Lower Member

1648.0 - 1650.0 (502.3 - 502.9) Limestone: calcilutite (cream), dolomitic (tan); abundant coarse-grained oolites, coralline (*Actinastrea*) fossils; earthy to dense, jointed and brecciated, bitumen stained on partings and in joints.

1650.0 - 1650.5 (502.9 - 503.1) Shale: dark grey, noncalcareous, blocky.

GRAVELBOURG FORMATION

1650.5 - 1657.5 (503.1 - 505.2) Dolostone: cryptocrystalline buff, faintly bedded; interbedded and intermixed with tan calcilutite and grey cryptocrystalline limestone, the latter as irregular nodules and the former as debris infilling solution joints and large cavities; (recovery 70%).

1657.5 - 1659.0 (505.2 - 505.7) No recovery.

1659.0 - 1659.5 (505.7 - 505.8) Dolostone: as at 1650.5 ft.

1659.5 - 1660.0 (505.8 - 506.0) Limestone: cryptocrystalline, dense, dark grey, fractured; nodular, bitumen-coated bodies lined with dark grey claystone; overlies subordinate dark grey claystone; (recovery 70%).

1660.0 - 1661.5 (506.0 - 506.4) Limestone: microcrystalline, dense, oolitic and pelletal; buff mottled with dark grey; (recovery 70%).

1661.5 - 1662.5 (506.4 - 506.7) Limestone: calcilutite, buff, silty; dark grey, argillaceous and quartzose sandy over lower half; crumbly and disaggregated.

1662.5 - 1663.5 (506.7 - 507.0) Limestone: calcilutite, buff, earthy; interbedded with limestone: microcrystalline, medium grey, abundant bitumen-lined stylolites, bedding partings and large moldic cavities.

1663.5 - 1664.5 (507.0 - 507.3) Limestone: calcilutite, tan, earthy, disaggregated.

1664.5 - 1665.5 (507.3 - 507.6) Limestone: cryptocrystalline, dense, dark grey, marked by calcitic flame structures and irregular geodes; centimetre-scale interbed of calcilutite: tan, flow textured.

1665.5 - 1666.5 (507.6 - 507.9) Limestone and shale: brecciated.

1666.5 - 1669.5 (507.9 - 508.9) Limestone: microcrystalline, pelletal, dark grey, dense; calcilutite interbeds: tan, flamed, slopes 20° across core.

1669.5 - 1672.0 (508.9 - 509.6) Sandstone: quartzose, fine grained, dark grey, dolomitic, friable (recovery 50%).

1672.0 - 1678.5 (509.6 - 511.6) Mudstone: dolomitic, medium grey, massive, calcareous toward base; interbedded at 0.06 m intervals with limestone: dense, dark grey, mesocrystalline, ptygmatic and distorted.

1678.5 - 1680.5 (511.6 - 512.2) Limestone: microcrystalline, dense medium grey; abundant centimetre-diameter geodes; sharp, irregular contact.

1680.5 - 1681.0 (512.2 - 512.4) Shale: dark grey, papery, calcareous; bedded, granular lithic aggregates over upper half; sharp, basal contact.

WATROUS FORMATION

Upper Member

1681.0 - 1688.0 (512.4 - 514.5) Dolostone: cryptocrystalline, earthy, massive; 0.04 m thick, dark grey and grey-black bituminous shaly interbeds at 0.08 m intervals; argillaceous over lower 0.06 m; sharp basal contact.

1688.0 - 1688.5 (514.5 - 514.7) Limestone: cryptocrystalline, medium green-grey, dense; subordinate stringers of tan calcilutite; sharp, basal contact.

1688.5 - 1690.0 (514.7 - 515.1) Mudstone: dolomitic, medium green-grey, platy to blocky; minor stringers and ptygmatic lenses of coarsely crystalline white limestone.

1690.0 - 1696.0 (515.1 - 516.9) Mudstone: red variegated with green, noncalcareous; abundant large ptygmatic networked bodies, fracture fillings and nodules of white, coarsely crystalline calcite; scattered similar bodies but gypsiferous toward base.

Lower Member

1696.0 - 1724.0 (516.9 - 525.5) Mudstone: dolomitic, red variegated with green, massive; steep fractures dipping 60°, rare anhydrite blebs.

1724.0 - 1730.0 (525.5 - 527.3) Mudstone: dolomitic, red, massive; enterolithic anhydrite nodules exceeding 0.1 m in thickness at 1724.0 ft (525.5 m); smaller nodules and scattered lateral millimetre-thick anhydrite veinlets below.

1730.0 - 1738.0 (527.3 - 529.7) Mudstone: dolomitic, red; marked over upper half by 0.01 m thick, intersecting curved, laterally trending veinlets of fibrous gypsiferous anhydrite at intervals of 0.08 to 0.1 m; and over lower half by interbeds of lensoid, 0.03 to 0.06 m thick, coarsely crystalline, white anhydrite.

1738.0 - 1749.0 (529.7 - 533.1) Mudstone: dolomitic, red variegated with green, compaction distorted texture; sharp-edged, post-compactional vertical veins >0.82 m long and up to 0.02 m thick, and subsidiary lateral, mildly distorted veinlets, up to 0.02 m thick, of white, coarsely crystalline anhydrite.

1749.0 - 1772.0 (533.1 - 540.1) Mudstone: green; compaction distorted texture; interbeds at 0.6 m intervals of coarsely crystalline, nodular enterolithic anhydrite, from which at 1759 ft (536.1 m) radiate laterally and vertically sharp-edged veins <0.3 m long and 0.03 m thick.

1772.0 - 1778.0 (540.1 - 541.9) Mudstone: dolomitic, red and green variegated; trace of lamination, but mostly compaction distorted; lateral veins of fibrous anhydrite, 0.01 m thick at intervals of 0.3 to 0.6 m, microfaulted at 1775 ft (541.3 m).

1778.0 - 1780.0 (541.9 - 542.5) Mudstone: dolomitic, red; subordinate enterolithic and coarsely granoblastic anhydrite; laterally trending veins of fibrous anhydrite over lower half.

1780.0 - 1793.0 (542.5 - 546.5) Mudstone: dolomitic; red, massive; lateral fibrous anhydrite veins at 1780 to 1781 ft (542.5 to 542.8 m) and at 1788 to 1793 ft (545.0 to 546.5 m); generally contorted and compaction distorted; minor green-grey argillaceous dolomitic nodules.

1793.0 - 1806.0 (546.5 - 550.5) Mudstone: dolomitic, red, interbedded with current-bedded dolomitic, quartzose siltstone; bedding crenulated and distorted around anhydrite nodules; fibrous anhydrite veins up to 0.06 m thick alternate at 0.3 m intervals with zones of abundant nodular anhydrite.

1806.0 - 1809.5 (550.5 - 551.5) Mudstone: dolomitic, red, compaction distorted, massive, abundant nodular and granoblastic anhydrite.

1809.5 - 1831.0 (551.5 - 558.1) Sandstone: quartzose, very fine grained, argillaceous, calcite cemented, reddish tan, current bedded with flasers, low-angle cut and fill; mildly distorted throughout, dense, well cemented.

1831.0 - 1851.0 (558.1 - 564.2) Mudstone: calcareous, red; subordinate interbeds of reddish tan, argillaceous, calcite-cemented sandstone; abundant nodular granoblastic anhydrite; scattered thin anhydrite veins over lower 1 m; strongly contorted over basal 0.6 m.

1851.0 - 1853.5 (564.2 - 564.9) Sandstone: quartzose, very fine grained, argillaceous, calcite cemented, reddish tan; flow distorted and balled with minor interbeds of red, calcareous mudstone and rare fibrous anhydrite veins.

1853.5 - 1856.0 (564.9 - 565.7) Sandstone: quartzose, very fine grained, massive, argillaceous, dolomitic, light reddish grey; abundant coarse grains and grits of quartzose sand, feldspar and ironstone; wavy veinlets of fibrous anhydrite toward base.

1856.0 - 1860.5 (565.7 - 567.1) Mudstone: deep red, calcareous; detached laminae and lenticles of sandstone as at 1851 ft (564.2 m); sandstone as at 1853.5 ft (564.9 m) becomes dominant downward.

1860.5 - 1862.0 (567.1 - 567.5) Sandstone: as at 1809.5 ft (551.5 m).

1862.0 - 1869.0 (567.5 - 569.7) Mudstone: deep red, calcareous; minor compaction distorted, reddish tan, argillaceous, very fine-grained, quartzose sandstone flasers increases to subordinate downward; laterally trending fibrous anhydrite vein at 1864 ft (568.1 m).

1869.0 - 1884.0 (569.7 - 574.2) Sandstone: quartzose, very argillaceous, calcareous; subordinate coarse-grained quartz, white feldspar, deep brown ironstone; dark grey and red variegated, current bedded; over lower 1 m interbedded at 0.06 m intervals with sandstone: quartzose, very fine grained, argillaceous, calcite cemented, current bedded with climbing ripples; reddish tan; current rip-up clasts conspicuous over basal 0.03 m.

1884.0 - 1888.5 (574.2 - 575.6) Dolostone: argillaceous, light reddish grey, hard, dense, grading below upper 0.6 m into mudstone: dolomitic, red, hard, dense; fractured and veined with anhydrite over upper and basal 0.3 m; sharp, sloping basal contact.

DUPEROW FORMATION (Karst debris)

1885.5 - 1889.5 (575.6 - 575.9) Dolostone: cryptocrystalline, cream coloured, dense; annealed breccia of pebble and boulder size fragments, veined with minor crenulated veins of white fibrous anhydrite; irregular basal contact.

1889.5 - 1892.5 (575.9 - 576.8) Mudstone: dolomitic, increasingly argillaceous and quartzose silty downward, red variegated with green, flow-bedded along truncating annealed fractures.

1892.5 - 1893.8 (576.8 - 577.2) Anhydrite: coarsely crystalline, dense, translucent light grey; subordinate stringers of mudstone; includes dolomite fragments over basal 0.03 m; faulted basal contact.

1893.8 - 1895.6 (577.2 - 577.8) Rubble: dolomite, anhydrite and red dolomitic mudstone; dipping up to 30°, well indurated with partings along bedded mudstone.

1895.6 - 1902.1 (577.8 - 579.8) Dolostone: as at 1885.5 ft (575.6 m), but veins are white, coarsely crystalline anhydrite with open intergranular pore network; interbreccia space infilled with anhydrite.

1902.1 - 1903.1 (579.8 - 580.1) Sandstone: quartzose, very fine grained, finely cross bedded, densely cemented with dolomite, cream coloured; coarsely laminated with red and green, dolomitic, argillaceous mudstone; predominantly red over upper 0.6 m and green below; sharp, dipping fracture-controlled contact.

1903.1 - 1905.0 (580.1 - 580.6) Dolostone: argillaceous, medium green-grey to reddish grey downward; mostly an annealed cobble size breccia; dense; sharp contact.

1905.0 - 1908.0 (580.6 - 581.6) Mudstone: argillaceous, dolomitic, red, dense; medial, irregular lateral and low-angle sloping veins of white anhydrite.

1908.0 - 1912.5 (581.6 - 582.9) Breccia: green dolomitic mudstone and white, coarse crystalline anhydrite.

DUPEROW FORMATION (Proper)

1912.5 - 1915.0 (582.9 - 583.7) Anhydrite: massive, dark grey, coarsely crystalline; subordinate lenticles and stringers of medium grey, cryptocrystalline dolomite; sharp, basal contact.

1915.0 - 1917.0 (583.7 - 584.3) Dolostone: cryptocrystalline, dense, faintly laminated; scattered, black, bituminous incipient stylolites.

Stratigraphy and Palynomorph Biostratigraphy of the Lower Mannville Group, Western Saskatchewan and Eastern Alberta – Preliminary Report

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Papadimitriou, S. and Burden, E.T. (2000): Stratigraphy and palynomorph biostratigraphy of the lower Mannville Group, western Saskatchewan and eastern Alberta – preliminary report; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

1. Introduction

Oil and gas discoveries in widely spaced localities throughout Alberta and Saskatchewan have led to the use of a plethora of names for subsurface Lower Cretaceous strata (Figure 1). Where these strata are essentially flat lying and laterally continuous, correlations are straightforward. They are, however, difficult where multiple incisions have occurred, where paleotopographic highs are covered by thin deposits, and where deposits have different sediment provenances or represent different depositional environments within adjacent "valleys".

In the absence of substantive macrofossil evidence, palynomorph biostratigraphy offers significant opportunity to subdivide strata, to establish age relationships, and to test correlations in Lower Cretaceous strata of eastern Alberta and western Saskatchewan.

Previous palynology studies have identified abundant and diverse assemblages of terrestrial and marine palynomorphs in the Lower Cretaceous Mannville Group (Pocock, 1962; Singh, 1964; Norris, 1967; Vagvolgyi and Hills, 1969; Playford, 1971; Burden, 1984; Banerjee and Davies, 1988; and Burden and Hills, 1989). Dinoflagellates track a long and punctuated history of Early Cretaceous marine transgression in the Western Canada Basin. Spores and pollen, and in particular pollen from flowering plants, track major evolutionary events in earth history as coastal environments were periodically drowned. The reports by Burden (1984) and Banerjee and Davies (1988) independently offer evidence suggesting the Ostracode Zone is diachronous as is, by implication, the lower-upper Mannville contact. Furthermore, their reports indicate that the Ostracode Zone may be Barremian in age in southern Alberta and Montana. If true, testing these concepts with a biostratigraphic transect from southern Alberta to the heavy oil belt of Saskatchewan may lead to significant revision of current stratigraphic models and depositional histories. This transect will generate significant new information on the regional distribution of lower Mannville palynomorph species in western Canada.

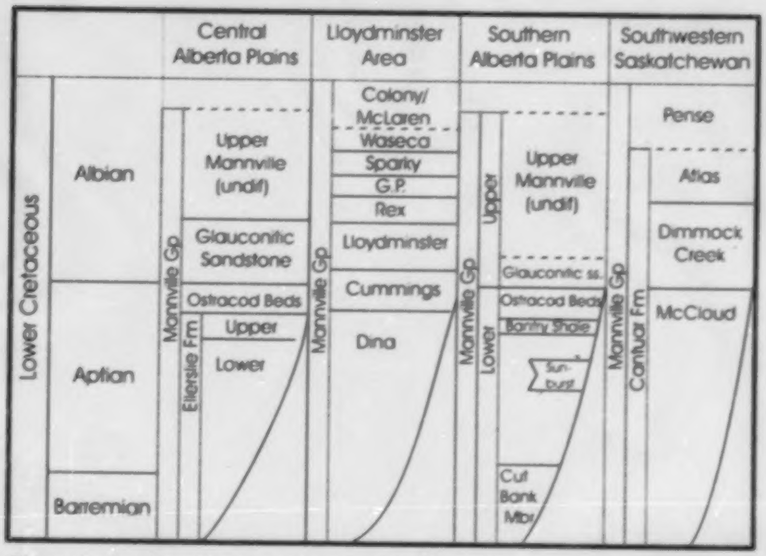

Figure 1 - Stratigraphic nomenclature of the Mannville Group in the study area (after Hayes et al., 1994).

2. Stratigraphic Framework

Glaister (1959) examined lithology of outcrop and core from southern Alberta and Montana and subdivided the Blairmore (Mannville) into Lower and Upper formations. The division between quartzose sandstones and cherty and glauconitic litharenitic sandstones was placed at the top of the Calcareous Member or Ostracode Zone as defined by Loranger (1951). Subsequent studies by Williams (1963) and Mellon

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(1967) confirmed details of this tripartite lithology in Alberta, identifying a complex channeled and unconformity-bounded stratigraphy which formed part of what we now recognize as an emerging foreland basin. Farther east in Saskatchewan, quartzose strata derived from the Canadian Shield form a significant fraction of the rocks of the Lower Cretaceous. Here, Vigrass (1977) employed an informal breakdown of the Mannville Group into lower, middle, and upper subgroups for the Lloydminster area. In this classification, the lower Mannville comprises the Dina and Cummings members; the middle Mannville, the Lloydminster, Rex, General Petroleums, and Sparky members; and the upper Mannville (well above the strata examined in this present study), the coal and cherty litharenite of the Waseca, McLaren, and Colony members. Christopher (1980, 1997) examined the Mannville stratigraphy in Saskatchewan and identified the Cantuar and Pense formations. He proposed that the Cantuar incorporate the Dina, Cummings, Lloydminster, Rex, General Petroleums, Sparky, and Waseca members, and that the Pense include the McLaren and Colony members.

Lithologically, the Mannville Group consists generally of interbedded shale and sandstone with minor coal. Mannville sediments were deposited in marine, estuarine, and fluviatile environments, in settings controlled by paleotopographic relief and changes in relative sea levels. Sediments were derived from local Paleozoic and Lower Mesozoic landforms, the Precambrian Shield, and rising volcanic uplands of the emerging Cordilleran orogen. In outcrop and core, Mannville Group strata show great lateral variation that developed as sea levels fluctuated through the Early Cretaceous. Internal architecture shows fluvial and tidal channels cutting into essentially flat surfaces. Evidently, little accommodation space was available. In absence of distinctive marker beds, detailed stratigraphic correlation of lower Mannville strata is difficult without closely spaced core control.

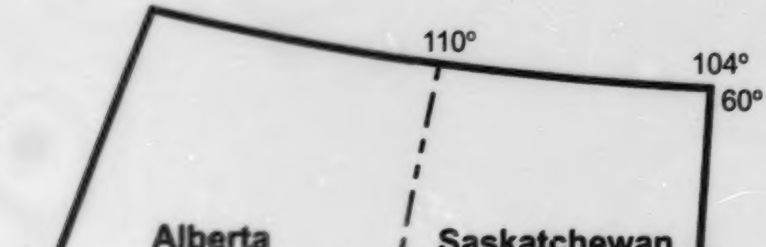

Figure 2 - Location of study area along the Saskatchewan/Alberta border.

3. Preliminary Results

Field work on this project included a detailed examination of 57 cores along a transect from southeast Alberta to west-central Saskatchewan (Figure 2). Table 1 outlines details for each core examined for this study, including the interval logged as well as the number of samples taken for palynological investigation. Samples were selected to provide coverage of each lower Mannville member and to capture changes between important lithologic units. Strata selected for collection were determined from geophysical log correlations and from lithological comparisons between cores. In Alberta, samples chosen for palynological processing were from cores of undifferentiated lower Mannville strata and the Glauconite sandstone. In Saskatchewan, the samples were constrained to those cores comprising Lloydminster, Cummings, and Dina members.

Samples were processed using standard palynological processing techniques. Samples were crushed to pea-sized fragments, of which 5 to 10 g were weighed into labelled beakers. To determine fossil concentration, *Lycopodium* spore tablets having concentrations of 12 542 ±375 were added to each sample. A 10% hydrochloric acid solution was added to each sample to remove carbonates. After approximately 24 hours, samples were washed with distilled water and then mixed with hydrofluoric acid to dissolve silicates. After another 24 hours, samples were washed again, following which an unsieved slide was prepared. Residues were then sieved with a 10 µm screen to remove fine organic fragments and clay. Following sieving, two additional slides were prepared for each sample; these provide information on organic maturation. Samples were then stained with Safranin O solution to enhance morphologic features of the specimens, after which another two slides were prepared. Highly organic samples, such as coals, were further oxidized with Schultze solution to remove humic matter and to lighten the material for easier microscopic observations.

Table 1 - List of cores logged and sampled.

Well Name	Well Location	Interval logged (m)	No. of samples taken
Shell Meaota	C13-17-46-17W3	498.0-584.0	10
Shell Dee Valley	11-18-48-21W3	479.0-588.5	28
Shell Husky Paradise Hill	A13-19-52-23W3	516.0-657.25	26
G&W Jordan Dankin	4-32-26-24W3	885.0-901.0	3
Shell Manitou	6-7-43-24W3	672.0-741.5	12
Saskoil Winter	10-28-42-25W3	645.0-675.0	6
H.J. McLaren #1	4-6-50-25W3	527.3-579.1	0
Husky McLaren #8	12-6-50-25W3	605.3-607.8	0
Mobil Tangleflags	A10-34-50-25W3	539.0-548.0	3
Mobil Tangleflags	6-36-50-25W3	524.9-569.7	4
Husky Tangleflags	A7-01-51-25W3	506.3-511.1	0
Husky Hillmond	111/5-7-51-25W3	532.0-547.0	5
Saskoil Gulf Senlac	1-6-39-26W3	783.2-800.6	6
Gulf Saskoil Senlac	B3-7-39-26W3	787.0-784.0	5
Shell Senlac	2-21-40-26W3	740.0-794.0	11
Saskoil PCI Marsden	A10-16-44-26W3	627.0-636.0	1
Wascana Marsden	A12-19-44-26W3	626.0-634.0	1
Saskoil PCI Marsden	A15-19-44-26W3	693.5-710.5	4
Conoco Neilberg	A3-11-46-26W3	596.0-612.0	5
G&W et al. Mantario N	A5-25-27-27W3	850.5-871.0	2
G&W Wascana	A13-32-27-27W3	897.0-915.0	4
Mantario N	A1-6-28-27W3	915.0-921.0	2
Saskoil Gulf Senlac	2-1-39-27W3	785.0-803.0	4
Gulf Saskoil Senlac	A4-1-39-27W3	786.5-804.5	5
Morgan Evesham	13-25-39-27W3	775.0-793.0	0
Calex et al. Court	A7-26-33-28W3	856.0-872.0	0
Texaco Court North	B6-6-34-28W3	872.0-891.95	3
Pex et al. Cactus LK	5-36-35-28W3	825.0-849.5	4
Pex et al. Cactus LK	5-1-36-28W3	806.0-815.0	3
Wascana Cuthbert	A2-2-27-29W3	933.5-948.5	3
Delhi Ba Antelope Hills #1	11-7-21-1W4	858.0-922.3	8
DS&W et al. Graindale	11-6-25-1W4	922.6-935.4	5
Wascana Alsask	5-13-27-1W4	891.0-906.0	7
Wascana Alsask	9-13-27-1W4	890.0-904.0	6
BP Sibbald	100/5-30-27-1W4	878.0-884.9	4
Compadre Sibbald	6-30-27-1W4	874.8-890.9	4
BP Sibbald D-32	10-32-27-1W4	842.0-851.0	3
Cass Alsask	14-02-28-1W4	816.5-852.5	6
BA et al. Antelope	10-12-30-1W4	766.6-774.2	2
Gardiner Compeer	10-24-33-1W4	843.0-851.5	6
Centennial Compeer	1-30-33-1W4	852.8-858.4	3
Anglo Royalite Kroy Acadia	7-25-23-2W4	881.5-890.6	0
D.S. Wetah Grandalee	10-13-25-2W4	915.9-932.1	6
Crestar Med. Hat	13-25-18-3W4	893.0-911.0	7
Crestar 102 Med. Hat	02/10-35-18-3W4	917.0-934.8	4
Ridgeway Wagner Cavendish	7-17-21-3W4	868.7-897.6	2
CMG Cyprus	6-1-8-4W4	1235.0-1250.0	4
Britalta DR Many Isl. #7	10-11-13-4W4	821.4-927.2	2
Gascan Med. Hat	14-9-14-4W4	878.0-895.0	5
Altex et al. Sapphire	16-5-2-5W4	1012.0-1021.0	2
TNR Omega Comrey	10-27-2-5W4	956.2-972.9	5
Shell et al. Sapphire	16-35-2-5W4	993.0-1002.0	0
Shell Bain	12-14-3-5W4	1034.0-1041.8	3
Triumph Manyberries	14-11-4-5W4	1048.0-1066.0	3
Anderson et al. Manyberries	4-35-4-5W4	1058.0-1076.0	0
Huber et al. Manyberries	6-3-5-5W4	1029.0-1045.0	3
Shell Manyberries	14-5-6-5W4	1055.0-1073.0	3

Preliminary examination of slides for species indicate the presence of the following taxa: *Baculatisporites, Cicatricosisporites, Cyathidites, Gleichiniidites, Impardecispora, Inaperturopollenites, Januasporites, Lycopodiacidites, Osmundacidites, Stereisporities*, and Taxodiaceae, as well as a number of bisaccates. These represent commonly reported Cretaceous plant fossils occurring in terrestrial settings.

Preliminary analysis of one distinctive coal horizon confirms that it can be correlated throughout the area. However, palynological assemblages suggest different coal-forming environments existed for the same coal. This implies facies variations and possible diachronism in the deposition of coaly sediments.

4. Further Work

Additional research will endeavor to clarify some of the complexities of correlating lower Mannville sediments using biostratigraphic controls. A comparative analysis of biostratigraphy and lithostratigraphy will attempt to determine whether strata and unconformities are easily identified with palynomorph biostratigraphy.

5. Acknowledgments

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The Paleoclimatological Significance of Albian (mid-Cretaceous) Sphaerosiderites from Eastern Saskatchewan and Western Manitoba

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Abstract

Reconstruction of paleoprecipitation, a critical variable in deciphering climate, has proven to be largely elusive. Therefore, the development and application of precipitation proxies are one of the most challenging aspects of exploring Earth system history in order to better understand climate and climate variability. Here we use carbon and oxygen isotopic analyses of sphaerosiderites (siderite spherules) formed in mid-Cretaceous wetland paleosols to reconstruct paleoprecipitaton along the eastern margin of the Western Interior Seaway (eastern Saskatchewan and western Manitoba). Our analysis includes palynostratigraphic, sequence stratigraphic, and soil micromorphologic observations of the Cantuar, Swan River, Pense, and Ashville formations, which support correlations between the sphaerosiderite-bearing locales. We discuss the various controls on mid-Cretaceous precipitation $\delta^{18}O$ chemistry, and argue that by identifying atmospheric vapour sources to the eastern margin of the seaway, we can quantify paleoprecipitation rates. We use sphaerosiderite-derived paleoprecipitation $\delta^{18}O$ estimates and the modern partly continental amount-effect relationship on precipitation $\delta^{18}O$ chemistry to estimate Late Albian precipitation rates in Manitoba and Saskatchewan of ~6000 mm or >200 inches/year. We conclude that these mid-Cretaceous high mid-latitude values are similar to modern tropical precipitation rates, and support the notion of an enhanced atmospheric hydrologic cycle for the mid-Cretaceous greenhouse world.

1. Introduction

The University of Iowa Cretaceous Research Group (UICRG) is constructing a paleolatitudinal precipitation $\delta^{18}O$ gradient for mid-Cretaceous North America based on oxygen isotopic analyses of sphaerosiderites formed in mid-Cretaceous wetland paleosols. Improved knowledge of the distribution of mid-Cretaceous precipitation $\delta^{18}O$ values will allow us to better understand the mid-Cretaceous greenhouse hydrologic cycle. Since the present-day latitudinal precipitation $\delta^{18}O$ gradient is well constrained (e.g. Dansgaard, 1964; Rozanski *et al.*, 1993, and others), enhanced awareness of the mid-Cretaceous climate may provide society with climatological insights into a globally warmed Earth.

In this paper, we present sequence stratigraphic and palynostratigraphic interpretations of the mostly Albian (mid-Cretaceous) Cantuar, Swan River, Pense, and Ashville formations (Fm), which tie sphaerosiderite oxygen isotope data from the Williston Basin and Manitoba Escarpment to our larger North American database. We also describe soil micromorphologies that support our contention that sphaerosiderites formed in wetland paleosols. Lastly, we provide the results of oxygen and carbon isotopic analyses of sphaerosiderites obtained from the Yarbo core (eastern Saskatchewan) and an outcrop and cores in western Manitoba, and discuss the paleoenvironmental implications of the data.

2. Background

a) Sequence Stratigraphic Setting

Under the warm climatic setting of the Cretaceous, eustatic sea levels were perhaps 650 m higher than present (Hancock and Kauffman, 1979). During this time in North America, the Cretaceous Western Interior Seaway (KWIS) spanned a region from the Arctic Ocean through the Northern Great Plains of Canada, most of the Rocky Mountains, Colorado Plateau, and Great Plains of the United States, to the Gulf of Mexico and northern Mexico. A connection through Hudson Bay existed as early as the Late Albian (White *et al.*, in press), and likely during subsequent sea-level highstands (Ziegler and Rowley, 1998). The KWIS epicontinental seaway was subject to at least nine second-order eustatic sea-level changes during this time (Kauffman and Caldwell, 1993).

Lower Cretaceous strata in southeastern Saskatchewan generally consist of a basal sandy group and an upper

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mainly marine shale group, similar to generalized stratigraphic trends observed in Alberta, Manitoba, North and South Dakota, and Montana (Price, 1963). However, distinct facies associations in southern Saskatchewan led Price (1963) to formally designate the coarse- and fine-grained units as the Cantuar Fm and Pense Fm, respectively. He interpreted the Cantuar Fm as having formed in a deltaic setting "during advancing Cretaceous inundation", with much of the lower part of the formation representing "reworked regolith from the pre-Cantuar emergence" (Price, 1963, p24-25). He noted that the contact between these two units is marked by a change from soft pale grey clay with siderite nodules to overlying carbonaceous shale or fine-grained sandstone, and considered the abrupt contact to represent a change to "much slower sediment accumulation in deeper water" perhaps "uniformly more saline than those of Cantuar deposition" (Price, 1963, p32-33).

Wickenden (1945) referred to the Lower Cretaceous sandy strata near the Saskatchewan-Manitoba border as the Swan River Fm. Given the Middle Albian (Playford, 1971; McNeil and Caldwell, 1981) to early Late Albian (Playford, 1971) age for Swan River strata in Saskatchewan and Manitoba, we interpret the Swan River Fm to have aggraded coincident with the regional rise in fluvial base levels associated with marine transgression of the Kiowa–Skull Creek Cycle, a well known second-order sea-level cycle in the Western Interior Basin. This eustatic sea-level rise began in the early Late Albian (Kauffman and Caldwell, 1993), culminating in sea-level highstand during the late Late Albian as the distribution of marine shale facies reached their maximum extent.

b) Sphaerosiderite Stable Isotope Chemistry

The term sphaerosiderite is used here to describe mostly sub- to millimetre-scale siderite spherules formed during early diagenesis in an environment of reduced iron, and in the absence of sulphate, where iron is sequestered in siderite (Ludvigson *et al.*, 1998a). Sphaerosiderites are often associated with red-mottled, rooted, kaolinitic mudrock paleosols. Sphaerosiderite-bearing paleosols are often interbedded with lignite or coal, and are interpreted to have formed in freshwater interfluves of alluvial plains (Witzke and Ludvigson, 1994). Meteoric sphaerosiderite lines (MSLs) provide a means for determining the δ^{18}O content of shallow meteoric phreatic fluids, and therefore serve as a proxy for paleoprecipitation δ^{18}O chemistry. MSLs are defined by variable δ^{13}C and invariant δ^{18}O values that reflect δ^{18}O fluid compositions in saturated soil and sediment. The relatively invariant siderite δ^{18}O values suggest that bacterially mediated fractionation effects are not important to sphaerosiderite formation, and that the temperature and δ^{18}O composition of groundwater in which the spherules form remain relatively constant. Sphaerosiderites appear to record formation in groundwater systems at depths where seasonal variability is within a few degrees of the mean annual temperature (Ludvigson *et al.*, 1998a).

Sphaerosiderites have been reported from modern reducing wetland soils (e.g. Stoops, 1983), and from many pre-Holocene deposits including mid-Cretaceous wetland paleosols (Ludvigson *et al.*, 1998a). They are also described from Cretaceous sandstones, e.g. Weimer and Sonnenberg (1989) and Hart *et al.* (1992), where they may be associated with major exposure surfaces at sequence boundaries. Siderite chemistry has been shown to vary as a function of Mg and Ca substitution for Fe in the siderite lattice; "pure" siderite forms in fresh-water environments, whereas "impure" siderite is more characteristic of marine influence (Mozley, 1989). Hart *et al.* (1992) demonstrated that mid-Cretaceous spherulitic siderite δ^{18}O chemistry varied not only with siderite purity, but also as a function of its sequence stratigraphic position, and therefore inferred relative water depths and inputs of fresh versus saline water. Therefore it is imperative to demonstrate a freshwater depositional setting to use sphaerosiderite δ^{18}O values as a proxy for meteoric phreatic water and precipitation δ^{18}O chemistry.

c) Sphaerosiderite-bearing Paleosol Micromorphology

An important micromorphological characteristic of wetland soils is low chroma in soil peds, or gleying. Gleying occurs when a soil remains wet, and Fe and Mn are reduced and removed from the profile (Stoops and Eswaran,1985). An important indicator of periodic soil saturation is soil mottling. Periodic soil saturation may result in reduction and gleying, followed by oxidation when the soil becomes unsaturated (Veneman *et al.*, 1976). Soil materials subject to only short periods of saturation may retain a high chroma since Fe is not removed from the matrix; more lengthy periods of saturation lead to Fe migration to soil ped surfaces where it may be precipitated as coatings (Stoops and Eswaran,1985).

In the Albian-Cenomanian Dakota Fm of the midcontinent United States, petrographic observations indicate that sphaerosiderites are primary features which crystallized as void-filling phreatic nodules in open root channels (Ludvigson *et al.*, 1998a). In addition, a grey mudstone facies containing abundant rounded siderite nodules adjacent to root traces in the Lower Cretaceous upper Blairmore Group of southwestern Alberta is interpreted to have formed under poorly drained conditions (McCarthy *et al.*, 1997), in the absence of sulphate. These observations from mid-Cretaceous paleosols are suggestive of strongly hydromorphic soils saturated with Fe-rich fresh groundwater, a setting in which Stoops and Eswaran (1985) have reported "radial siderite grains" associated with decaying plant fragments.

d) Paleoclimatological Implications of Sphaerosiderites

Sphaerosiderite-bearing kaolinitic mudrock paleosols associated with lignites and kaolinitic regolith in the Dakota Fm from the eastern margin of the KWIS were interpreted as having formed in a warm, humid climate

(Witzke and Ludvigson, 1994). The occurrence of lithologically similar, coeval deposits throughout North America (White *et al.*, in press) and the global distribution of mid-Cretaceous laterites (Sigleo and Reinhardt, 1988) support an interpretation of widespread subtropical to tropical conditions, and provides evidence for high precipitation rates since laterites form under precipitation regimes >1000 mm/year (Bardossy, 1981). These observations are generally supportive of model-derived estimates of the warm Cretaceous climate as having warm poles with no evidence for permanent ice, continental interiors with little seasonality, and globally averaged surface temperatures 6° to12°C higher than present (Barron, 1989).

The sphaerosiderite $\delta^{18}O$ paleorecord from British Columbia to Kansas has been shown to exhibit an overall depletion in $\delta^{18}O$ from 30° to 55° paleonorth (White *et al.*, 1998). Ludvigson *et al.* (1998b) concluded that this depletion with increasing paleolatitude is steeper than the gradient modeled for hypothetical sphaerosiderites forming from modern soil waters. Given lower mid-Cretaceous paleolatitudinal temperature gradients, e.g. Barron (1989), they suggested the steeper sphaerosiderite $\delta^{18}O$ gradient is the result of higher rain-out effects in the Albian hydrologic cycle (Ludvigson *et al.*, 1998b). White *et al.* (in review) focus on the eastern margin of the KWIS and interpret a consistent ~4‰ (SMOW) depletion in the Albian-Cenomanian precipitation $\delta^{18}O$ proxy record relative to the modern gradient as representing an amount effect on mid-Cretaceous precipitation, and use this to estimate annual paleoprecipitation rates.

3. Methodology

Mid-Cretaceous sphaerosiderite samples were obtained from the Yarbo core in eastern Saskatchewan, from an outcrop along the Swan River, and the M-9-78 and M-10-78 cores in western Manitoba. Ten sphaerosiderites were microdrilled from each horizon, and analyzed for carbon and oxygen isotopes as outlined in Ludvigson *et al.* (1998a).

Late Albian precipitation $\delta^{18}O$ (SMOW) values were calculated from the sphaerosiderite $\delta^{18}O$ (PDB) values, first using equilibrium fractionation factors for siderite-water, and phosphoric acid liberated CO_2-siderite defined as a function of temperature (Carothers *et al.*, 1988). To establish the temperature for a given sample, longitudinally averaged mean annual temperature profiles were constructed along the eastern margin of the KWIS using Late Albian model-derived temperatures from Poulsen (1999). Since the sphaerosiderite $\delta^{18}O$ value is a function of these fractionation factors and the $\delta^{18}O$ value of the shallow groundwater from which the siderite precipitated, the sphaerosiderite-derived $\delta^{18}O$ (SMOW) values record mean annual Late Albian precipitation $\delta^{18}O$ values.

4. Results and Discussion

Our field work in Saskatchewan and Manitoba is part of a much larger project to map the paleolatitudinal distribution of sphaerosiderite $\delta^{18}O$ values for the mid-Cretaceous greenhouse world. High-resolution correlation is necessary to ensure that sphaerosiderite $\delta^{18}O$ values obtained from discrete paleosol horizons at one locale can be correlated to other distant locales. To better facilitate high-resolution correlations between these non-marine paleosol horizons, detailed regional palynostratigraphic and sequence stratigraphic frameworks are constructed for the sampling locales. The following discussion outlines the results of our paleopalynological assays and lithologic/sequence stratigraphic correlation of outcrops and cores from the study area. In addition, soil micromorphological descriptions of the sphaerosiderite-bearing paleosols and interpretations of mid-Cretaceous sphaerosiderite-derived precipitation $\delta^{18}O$ values are presented.

a) Palynostratigraphy

Paleopalynological assay results of the samples are presented in Table 1, and their geographic and stratigraphic locations shown in Figure 1. In general, all of the samples contain Late Albian palynomorph assemblages as described in studies of the Dakota Fm in the midwestern United States (Ravn and Witzke, 1995), the Mattagami Fm in the Moose River Basin, Ontario (Telford *et al.*, 1991), the Swan River Fm in Saskatchewan and Manitoba (Playford, 1971), the Cretaceous Rainy River outlier of southwestern Ontario (Zippi and Bajc, 1990), and Lower Cretaceous terrestrial palynomorphs of Western Canada (Burden and Hills, 1989). These taxa are consistent with our sequence stratigraphic correlations presented in Figure 1.

The sample collected from the Yarbo core (389.5 m, 1278 ft) contains an abundance of the uncommon trilete spore *Murospora wirthii*, and also contains the algal forms *Lecaniella foveata* and *Schizocystia rugosa*. This low-diversity *M. wirthii* non-marine algal-rich assemblage is similar to samples from the Swan River Fm in Manitoba discussed below, and may record an unusually wet terrestrial paleoenvironment. A sample from a clay pit near Ste. Rose du Lac contains *M. wirthii*, but in greater numbers than in M-9-78 and M-10-78. Associated algal forms, *S. rugosa* and *L. foveata*, are less common, but overall the assemblage is very similar to that observed in the nearby cores. The abundance of freshwater algal palynomorphs in the Swan River Fm (see Table 1) underscores the ubiquity of wetland environments in the Albian coastal lowlands of Manitoba and Saskatchewan, and further corroborates the depositional setting inferred for sphaerosiderite formation in saturated wetland soils.

In the Pine River core, the presence of *S. rugosa* and *L. foveata* in sample 48.6 suggests a similarity to the Yarbo core sample and the Swan River Fm, although they are much less common in the Pine River Core.

Table 1 - Albian Palynomorphs, Saskatchewan-Manitoba.

	1	2	3	4	5	6	7	8
Terrestrial Spores and Pollen								
Aequitriradites spinulosus						x		
Annulispora sp.					x			
Antulsporites sp.						x		
Balmeiopsis limbatus					x	x		
Balmeisporites holodictyus						x		
Biretisporites potoniei						x		
Callialasporites dampieri						x		
Camarozonosporites ambigens					x	x	x	x
Camarozonosporites wrennii						x		
Cicatricosisporites apicanalis								x
Cicatricosisporites australiensis						x		x
Cicatricosisporites claricanalis							x	
Cicatricosisporites mediostriatus						x		x
Cicatricosisporites orbiculatus							x	
Cicatricosisporites venustus					x	x		x
Cicatricosisporites sp.					x	x		x
Cingulatisporites cf. *levispeciosus*		x						
Cingutriletes congruens					x			
Clavifera cf. *triplex*			x	x				
Concavissimisporites punctatus					x	x		x
Corollina torosa						x		
Cycadopites sp.		x	x					
Deltoidospora hallii	x	x	x		x	x	x	x
Deltoidospora minor					x			
Densoisporites circumundulatus					x			
Densoisporites microrugulatus			x		x			x
Distaltriangulisporites perplexus								x
Echinatisporis varispinosus						x		
Foveomonocolpites sp.		x	x	x				
Foveosporites subtriangularis					x			
Gleicheniidites senonicus	x	x	x	x	x	x		x
Granulatisporites michinus								x
Impardecispora excavata					x			
Impardecispora marylandensis					x	x		x
Impardecispora trioreticulosa							x	x
Ischyosporites cf. *crassimacerius*								x
Ischyosporites disjunctus								x
Ischyosporites pseudoreticulatus						x		x
Kraeusellisporites cf. *breviculus*							x	
Laevigatosporites gracilis			x					
Laevigatosporites ovatus	x	x		x		x	x	

	1	2	3	4	5	6	7	8
Freshwater Algal Spores								
Lecaniella foveata	x	x	x	x	x			
Ovoidites parvus		x						
Ovoidites australiensis				x				
Ovoidites sp.					x			
Schizocystia rugosa	x	x	x		x			
Marine Palynomorphs								
Alterbidinium? sp.					x			x
Areoligera sp.								x
Batioladinium jaegeri						x		
Cassiculosphaeridia? sp.					x			
Chlamydophorella nyei						x		
Circulodinium sp.						x		x
Cometodinium? sp.					x			
Crassosphaera sp.						x		x
Cribroperidinium edwardsii							x	
Cribroperidinium sp.						x		x
Cyclonephelium cf. *compactum*						x		
Cymatiosphaera sp.					x			
Fromea amphora						x	x	
Fromea fragilis							x	
Impletosphaeridium sp.					x	x	x	
Odontochitina operculata					x	x	x	
Oligosphaeridium albertense					x			x
Oligosphaeridium complex						x	x	x
Oligosphaeridium totum						x		
Ovoidinium verrucosum							x	
Palaeoperidinium cretaceum					x	x	x	
Pseudoceratium interiorense							x	
Pseudoceratium cf. *pelliferum*								x
Pseudoceratium polymorphum						x		
Pseudoceratium cf. *securigerum*								x
Pterodinium cf. *aliferum*					x			
Pterospermella sp.					x			
Spinidinium sp. (small, pale)							x	
Spiniferites ramosus						x	x	
Spiniferites sp.						x		
Stiphrosphaeridium anthophorum							x	
Veryhachium sp.							x	

	1	2	3	4	5	6	7	8
Terrestrial Spores and Pollen (continued)								
Lycopodiacidites canaliculatus		x						
Lycopodiacidites sp.				x				
Microreticulatisporites uniformis						x		
Murospora wirthii	x	x	x	x				x
Natronaspora foeda		x	x					
Neoraistrickia robusta						x		
Neoraistrickia sp.			x					
Nicholsipollis mimas				x	x	x	x	
Nodosispora cf. *stellantis*							x	
Nodosisporites sp.					x			
Osmundacidites wellmanii					x	x		
Parvisaccites radiatus				x			x	
Petalosporites quadrangulus			x					
Pilosisporites trichopapillosus							x	
Pilosisporites sp. (sm. crowded pilla)		x						
Plicatella cristata					x		x	
Plicatella jansonii				x	x			
Plicatella cf. *tricornitata*								x
Plicatella witzkei						x		
Podocarpidites sp.	x		x		x	x		
Pristinuspollenites inchoatus							x	
Pristinuspollenites sulcatus					x		x	
Reticulosporis reticulatus		x						
Retitriletes austroclavatidites					x			x
Retitriletes singhii					x	x	x	
Retitriletes sp.	x				x		x	
Rugubivesiculites convolutus						x		
Rugubivesiculites reductus	x			x				
Rugubivesiculites rugosus	x	x		x	x		x	
Sabalpollenites scabrus				x				
Schizosporis reticulatus				x		x		
Sestrosporites pseudoalveolatus	x			x	x	x	x	
Staplinisporites caminus								x
Stereisporites sp.	x		x					
Taxodiaceaepollenites hiatus		x				x		
Tigrisporites reticulatus							x	
Triporoletes cenomanianus							x	
Triporoletes reticulatus					x			
Triporoletes simplex							x	
Tsugaepollenites sp.			x					
Indet. bisaccate gymnosperm pollen	x	x	x	x	x	x	x	x

Notes:

1. Yarbo #17S core (depth 389.5 m, 1278 ft), 1-24-20-33W1, Saskatchewan.
2. Ste. Rose du Lac clay pit (carbonaceous mudstone), 15-04-23-15W1, Manitoba.
3. Ste. Rose du Lac M-9-78 core (depth 9.1 m), 15-04-23-15W1, Manitoba.
4. Ste. Rose du Lac M-10-78 core (depth 9.35 m), SW4-10-23-15W1, Manitoba.
5. Pine River M-8-78 core (depth 48.6 m), 4-32-32-22W1, Manitoba.
6. Pine River M-8-78 core (depth 34 m), 4-32-32-22W1, Manitoba.
7. Armit River exposure, McNeil and Caldwell (1981) Locality MC-35 (below first bentonite), 15-24-44-30W1, Saskatchewan.
8. Little Woody River, near National Mills, McNeil and Caldwell (1981) Locality MC-36 (upper Newcastle), 9-22-44-29W1, Manitoba.

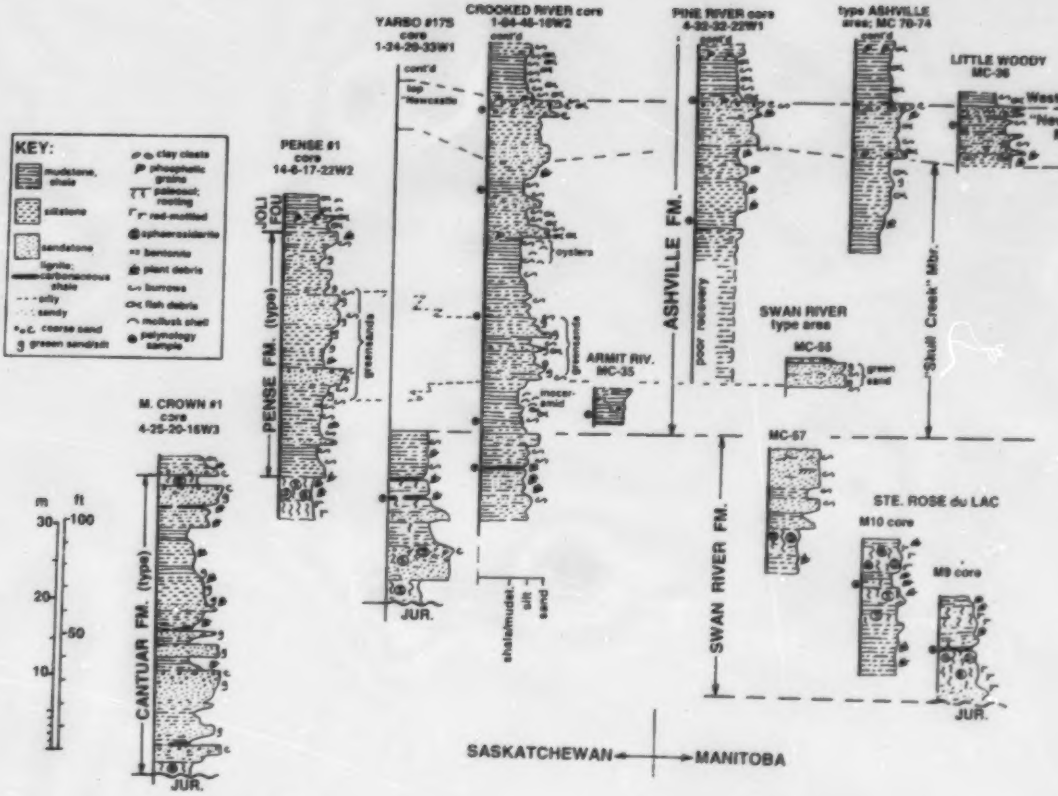

Figure 1 - Lithostratigraphic and sequence stratigraphic cross-section for the Albian Cantuar Fm and Pense Fm in eastern Saskatchewan, and the Swan River Fm and Ashville Fm in western Manitoba.

Characteristic Late Albian taxa in the Pine River core include *Densoisporites circumundulatus, Impardecispora marylandensis, I. excavata, I. trioreticulosa, Plicatella jansonii, Nicholsipollis mimas*, and the dinoflagellate cyst *Batioladinium jaegeri*. The presence of *I. excavata* in the core, in particular, indicates a limited stratigraphic range within the Late Albian (Ravn, 1995).

At outcrop section MC-35, the Late Albian marker dinoflagellate cyst species *Ovoidinium verrucosum* dominates the assemblage, along with other marine forms. In addition, the characteristic Albian spore and pollen taxa *Pilosisporites trichopapillosus* and *N. mimas* are present. A sample obtained from the Little Woody outcrop section contains a variety of Late Albian non-marine palynomorph taxa including *I. marylandensis, I. trioreticulosa, Staplinisporites caminus, Concavissimisporites punctatus, Distaltriangulisporites perplexus, N. mimas, M. wirthii*, and *Ischyosporites disjunctus*. This sample also contains relatively common dinoflagellates dominated by unidentified *Cribroperidinium* species. The Ashville Fm samples from both outcrops contain abundant marine dinoflagellate cysts resembling those from the Kiowa Fm in Kansas (Bint, 1986).

b) Sequence Stratigraphy

The stratigraphic framework for the paleoclimatological reconstruction is presented in Figure 1. Price's (1963) type sections for the Cantuar Fm and Pense Fm (Tidewater Matador Crown No. 1 well, and Sohio Canadian Devonian Pense No. 1 well, respectively) are included. In the Yarbo No. 17 core from eastern Saskatchewan, sphaerosiderite-bearing horizons are correlated to siderite granule-bearing horizons (described by Price, 1963) at the base of the Cantuar Fm.

Sphaerosiderites from rooted kaolinitic mudrock paleosols were sampled at McNeil and Caldwell's (1981) outcrop section 57 (MC-57, Figure 1), which was placed in the upper Swan River Fm because of the presence of marine-influenced sedimentation (burrowed fabrics, possible tidalites, and flaser bedding). In addition, on the basis of burrowed fabrics stratigraphically above sphaerosiderite-bearing paleosols, the lowermost portion of the Crooked River core (eastern Saskatchewan) was assigned to the upper Swan River Fm (White *et al.*, 1999). Near the top of the upper Swan River succession in eastern Saskatchewan, a possible sequence boundary, capped by pyritic, calcite-cemented beds in the Crooked River core (White *et al.*, 1999), suggests renewed sea-level rise preceding Kiowa–Skull Creek highstand deposition. It is proposed that this surface may be sequence boundary 7 in the upper Cantuar Fm, implying that much of the overlying upper Swan River Fm in eastern Saskatchewan may represent estuarine fills similar to that interpreted for the Cantuar Fm (Leckie *et al.*, 1997). The basal unit of the Pense Fm in southwestern Saskatchewan represents marine transgression and ravinement above the Cantuar Fm (Leckie *et al.*, 1997), so the uppermost Swan River unit may also contain this ravinement surface.

Two cores (M-9-78 and M-10-78) drilled by Manitoba Energy and Mines near Ste. Rose du Lac penetrate the Swan River Fm (Figure 1). The absence of marine indicators and the abundance of red-mottled paleosols in these cores suggest a lower position within the formation. Reworked limestone pebbles in the basal part of the M-9-78 core may suggest a position close to the Jurassic unconformity (Figure 1).

In the Crooked River core from eastern Saskatchewan, the Swan River Fm is sharply overlain by black shale and siltstone of the Joli Fou Fm (White *et al.*, 1999), which correlates to the Skull Creek Member (Mbr) of the Ashville Fm (early Late Albian) in the Manitoba Escarpment where this contact is disconformable (McNeil and Caldwell, 1981). The abrupt disconformable nature of the Joli Fou/Cantuar-Pense formations contact probably formed during the maximum rate of sea-level rise in the Kiowa–Skull Creek Cycle. Leckie *et al.* (1997) interpreted the regional package of shale and siltstone above the disconformity to have been deposited in a shallow-marine/shelf- to distal-shoreface setting based on stratigraphic and lithofacies reconstructions.

The lower portion of the Skull Creek Mbr of the Ashville Fm in the Yarbo core contains greensands and silts which probably correlate to greensand in the Pense Fm, and to Spinney Hill Mbr greensands in the Joli Fou Fm in the Crooked River core (Figure 1). The greensand interval at Locality MC-55 is also included within the lower Ashville Fm (Figure 1) because of lithologic similarities with Spinney Hill greensands, although McNeil and Caldwell (1981) assigned this exposure to the upper Swan River Fm.

Several of McNeil and Caldwell's (1981) measured sections are included in the regional cross-section (Figure 1) to further delineate correlations within the Ashville Fm. The Pine River core was placed in the Ashville Fm based primarily on limited palynological evidence, particularly the presence of abundant marine dinoflagellates (Table 1) not seen in the Swan River Fm. In addition, terrestrial spores and pollen from the lower core sample (48.6 m) share more common species with other lower Ashville samples (70%) than with the Swan River samples (22%, all long-ranging forms) (Table 1; also White *et al.*, 1999). The distinctive spore, *M. wirthii*, is abundant in all Swan River samples, but has not been identified in the Pine River core. Furthermore, placement of the Pine River core within the Ashville Fm aligns the interval containing coarse sand with similar lithologies in the upper Newcastle Sandstone Member (Viking Fm) at nearby localities (Figure 1). This coarse-grained interval in the Pine River core is capped by pyritic, grey, fish-scale-bearing marine shale, with phosphatic clasts at the base. Identical facies relations are seen at the Newcastle (Viking)-Westgate contact elsewhere in Manitoba and Saskatchewan (Figure 1).

c) Soil Micromorphology

The white to light grey matrix surrounding sphaerosiderites is characteristic of low redox conditions formed as gleysols (Mack *et al.*, 1993). The key to maintaining low redox conditions in soils is wetness; indicators of prolonged soil saturation are pedogenic siderite, asepic or granular unstriated fabrics, and massive structure (Retallack, 1981). Plant remains, particularly roots, can be preserved under saturated conditions because of prolonged anaerobic conditions (Stoops and Eswaran, 1985). The paleosol ordering scheme of Mack *et al.* (1993) further classifies gleysols on the basis of mineralogic and pedogenic features including horizonation and the lack of soluble mineral accumulation, insoluble mineral illuviation, *in situ* mineral alteration, and organic matter content.

Eh-pH stability fields show that siderite forms under reducing, near-neutral conditions free of dissolved sulphate (Garrels and Christ, 1965); therefore, sphaerosiderites provide some of the best evidence for freshwater reduced paleosols. Siderite commonly occurs as spherically shaped radial crystal aggregates (sphaerosiderite) in the Swan River Fm paleosols, although a lath-shaped siderite micromorphology is locally present (Figure 2A). For example, sub-millimetre siderite crystal laths are common in red-mottled mudstones in the M-10-78 core (Ste. Rose du Lac). This siderite morphology resembles individual acicular crystals seen within the radial crystal fabrics of sphaerosiderites, and the lath-shaped morphology may represent a phase preceding sphaerosiderite growth (twinning and intergrowth of laths would produce a radial crystal fabric). A sphaerosiderite exhibiting a "pseudouniaxial cross", and a birefringent halo in a granular unstriated matrix is also shown in Figure 2A. The birefringent halo may have formed as translocated clays accumulated at a boundary between the sphaerosiderite and the surrounding matrix, or by clay mineral reorientation during displacive sphaerosiderite growth.

Several sphaerosiderites in a granular to cross-striated matrix with sepic-plasmic fabrics are visible in Figure 2B. The weakly cross-striated matrix and sepic-plasmic fabric are likely indicative of stresses related to wetting and drying (Brewer, 1976), although cross-striated fabrics superimposed on an originally speckled fabric have been described in hydromorphic soils in the humid tropics of central Africa (Stoops and Eswaran, 1985). In Figure 2C, a sphaerosiderite in granular to cross-striated matrix from the same horizon as sphaerosiderites in Figure 2B also shows microlaminated pore infillings in the soil matrix. The presence of clay coatings, or illuvial clay, requires that water percolated into the soil and dried out so that the translocated clay was retained. Yellow and silty clay coatings suggest that free drainage alternated with phases of poor drainage, saturation (McCarthy *et al.*, 1998), and hydromorphic degradation. Alternatively, clay, silt, and humic laminae can also form as flood coatings, particularly in deeply flooded soils, as have been described from the monsoonal setting of the Ganges floodplain (Brammer, 1971).

In Figure 2D, coalesced sphaerosiderites in a granular unstriated matrix are partially engulfed by red mottles. The combination of these mottles with oxidized sphaerosiderite rims provides evidence for a post-sphaerosiderite formation episode of aeration, oxidation and precipitation of iron minerals in the soil. Red, yellow or brown mottles in a grey-green matrix, commonly with iron and manganese nodules, are indicators of varying redox conditions under a fluctuating water table. A mottled horizon may still be classified as a gleyed paleosol if mottles are not the only evidence of gley (Mack *et al.*, 1993).

d) Sphaerosiderite Petrography and Isotope Chemistry

Raw carbon and oxygen isotope data (relative to PDB standard) from two samples from the Yarbo core, two samples from the M-9-78 core, and one sample from outcrop MC-57, are presented in Figure 3. Sphaerosiderite $\delta^{13}C$ values ranging from ~0 to -16‰ are suggestive of oxidized organic matter, dissolved atmospheric CO_2, and perhaps marine dissolved inorganic carbon (DIC) as sources of bicarbonate for siderite formation. Sphaerosiderite $\delta^{18}O$ values ranging from ~-3.5 to -9.5‰, are discussed in more detail below.

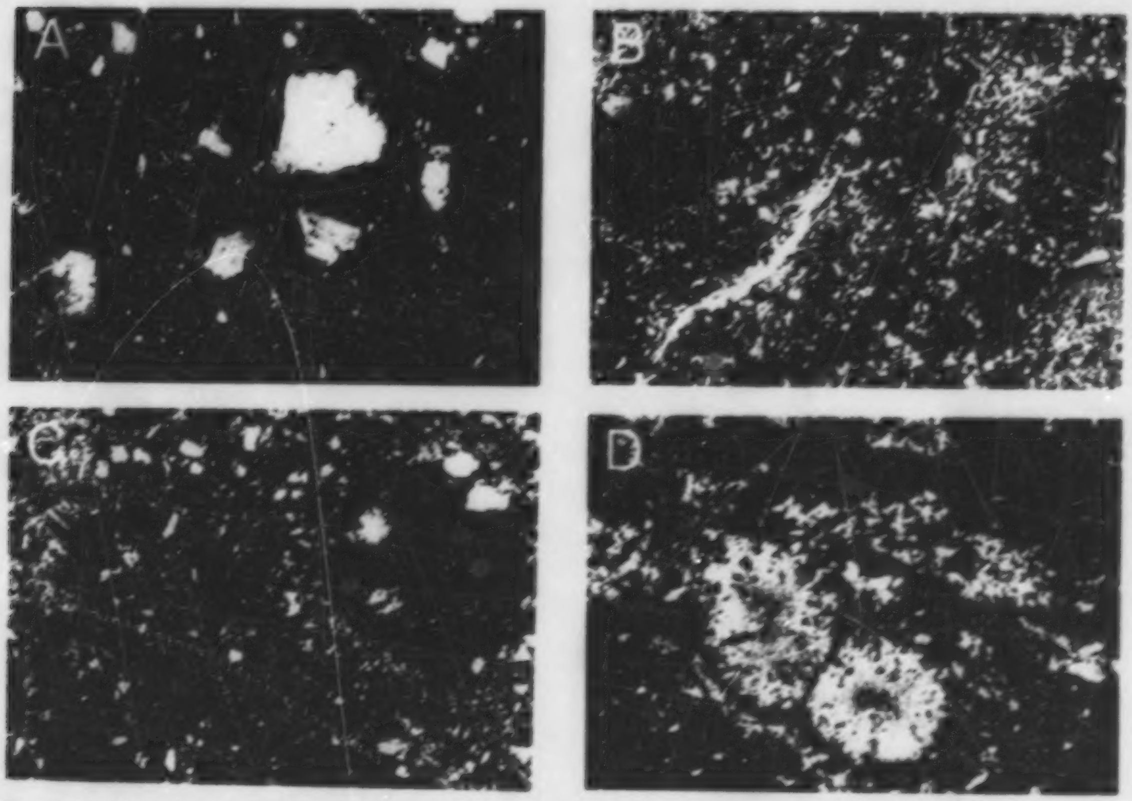

Figure 2 - Thin section photomicrographs (in cross-polarized light) of sphaerosiderites and paleosol micromorphologic features from the Swan River Fm in eastern Saskatchewan and western Manitoba. A) Juxtaposed sphaerosiderite and lath-shaped siderite from the Manitoba Energy and Mines core M-9-78, 9.55 ft; note the sphaerosiderite "pseudouniaxial cross", and the birefringent halo in the granular unstriated matrix (width of view = 1.3 mm); B) Several sphaerosiderites in a granular to cross-striated matrix from outcrop MC-57 on the Manitoba Escarpment; note sepic-plasmic fabrics manifested as thin wispy streaks trending from the bottom left toward the centre of the field of view (width of view = 3.0 mm); C) A sphaerosiderite from the same horizon as 2B with the same granular to weakly cross-striated matrix. Yellow to light orange microlaminated pore infillings occur to the far left in the photograph, and small pyrite inclusions exist in the sphaerosiderite core (width of view = 1.3 mm) and D) Two coalesced sphaerosiderites in a granular unstriated matrix from the Yarbo core at 1314.8 to 1315.1 ft; note that the sphaerosiderites have corroded margins and oxidized hematitic rims, and are partially engulfed by red iron oxide mottles (width of view = 1.3 mm).

The MC-57 sample, earlier included in the analysis of Ludvigson *et al.* (1998a), is characterized by relatively invariant $\delta^{13}C$ and $\delta^{18}O$ values, and a mean $\delta^{18}O$ composition of -5.5 ±0.1‰ (Figure 3). The precipitation $\delta^{18}O$ estimate for this horizon is based on this mean value. Samples 9.6 and 11.2 from the M-9-78 core also show relatively invariant $\delta^{13}C$ and $\delta^{18}O$ values, with $\delta^{18}O$ compositions of -4.2 ±0.3‰ and -5.4 ±0.2‰, respectively (Figure 3). The stratigraphic separation between these samples is small, which suggests they may represent a single paleosol. Viewed together, the general trend in $\delta^{18}O$ values from these samples may exhibit characteristics of a fluid mixing curve (Figure 3). Therefore, the precipitation $\delta^{18}O$ estimate for the M-9-78 core is based on its most depleted sphaerosiderite $\delta^{18}O$ value, i.e. -5.8‰.

Samples from the Yarbo core are somewhat problematic. Sample 1314.8 has $\delta^{18}O$ values ranging from about -3.5 to -6.5‰, and a mean $\delta^{18}O$ composition of -5 ±1.0‰, whereas $\delta^{18}O$ values in sample 1315.5 range from about -3.5 to -9.5‰, with a mean $\delta^{18}O$ composition of -7.2 ±2.1‰ (Figure 3). The difference between these mean sphaerosiderite $\delta^{18}O$ values may be explained by atmospheric vapour source or the paleoprecipitation amount effect variations through time. The stratigraphic separation between the two samples is small, so the horizons may have formed as a single paleosol. In this case, the more enriched values of the stratigraphically higher 1314.8 sample may record sphaerosiderite precipitation from the evaporatively influenced upper water table, whereas sample 1315.5 records fully saturated conditions free of evaporative effects. This interpretation is compatible with observations of oxidized hematitic rims on many of the Yarbo sphaerosiderites (Figure 2D). Interestingly, the $\delta^{18}O$ values from the 1314.8 sample overlap the range in $\delta^{18}O$ values from sample 1315.5 (Figure 3), suggestive of an upsection fluid mixing curve. This provides a second hypothesis for the perceived relationship between $\delta^{18}O$ values for the samples. The general trend of this hypothetical mixing curve is suggestive of an upsection increase towards oceanic $\delta^{18}O$ values of -1.2‰ for an ice-free world (Shackleton and Kennett, 1975), which has been applied to KWIS isotopic studies (Pagani and Arthur, 1998). If valid, this trend in Yarbo core sphaerosiderite $\delta^{18}O$ values is compatible with covarying $\delta^{13}C$ values toward marine DIC values, and upsection facies stacking patterns recording relative sea-level rise.

Alternatively, the Yarbo sphaerosiderites may pose an interesting diagenetic problem. Sphaerosiderites in these horizons have corroded margins suggestive of alteration by a diagenetically aggressive fluid (Figure 2D). In addition, the preservation of spherulitic structure is variable; some are good spherulites, some have ghost spherulitic structure reorganized into a coarser blocky mosaic, and some display unit crystal extinction. Viewed together, the Yarbo 1315.5 and 1313.8 data may form a continuous diagenetic trend (Figure 3). Note that the Yarbo sphaerosiderites occur in a paleosol at the top of a sandstone. Heavy $\delta^{18}O$ end-member sphaerosiderites may preserve a geochemical "memory" of the original soil-formed sphaerosiderite compositions, whereas those at the light $\delta^{18}O$ end-member may represent recrystallized siderites that equilibrated with a regional groundwater flow system during early shallow burial. This conceptual model is analogous to the groundwater system described by Phillips *et al.* (1999a, 1999b) on the basis of light $\delta^{18}O$ end-member siderite values of -9.8‰ from our newly recorrelated tidalite sandstones in the Ashville Fm in the Pine River core in Manitoba.

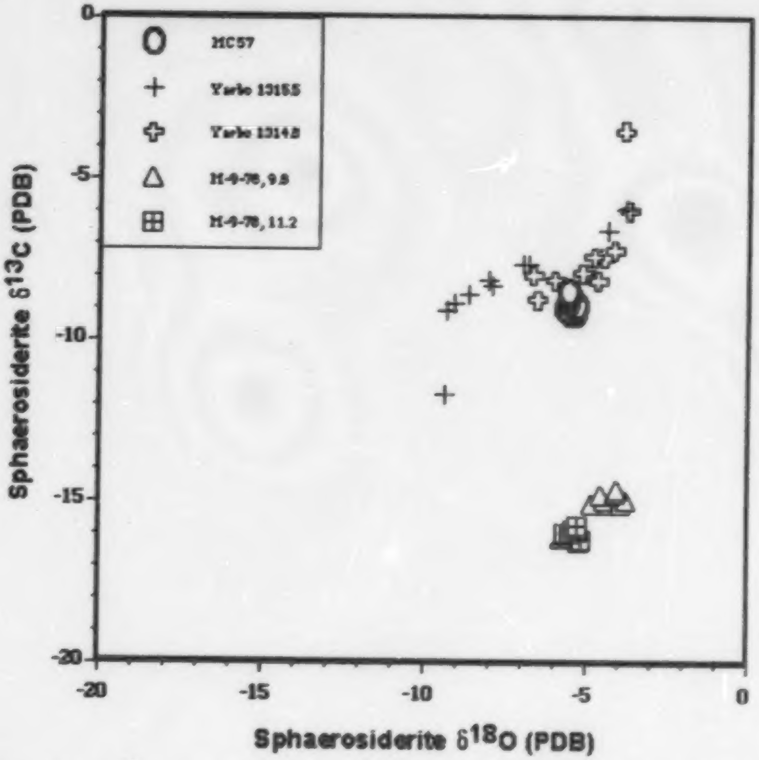

Figure 3 - Carbon and oxygen isotope cross plot of sphaerosiderite samples from the Albian Swan River Fm in eastern Saskatchewan and western Manitoba.

Nonetheless, based on soil micromorphological characteristics and the presence of various freshwater algal palynomorphs, we are confident that some of the sphaerosiderites in the Yarbo core record meteoric phreatic fluid δ^{18}O chemistry. For these reasons, the calculated precipitation δ^{18}O estimates for the Yarbo core are from its most depleted sphaerosiderite δ^{18}O value, i.e. -9.4‰.

Using the values discussed above, Late Albian precipitation δ^{18}O (SMOW) values are calculated as ~9.7‰ for outcrop MC-57, ~-10‰ for the M-9-78 core, and ~-13.6‰ for the Yarbo core. The sphaerosiderite δ^{18}O and calculated precipitation δ^{18}O values for outcrop MC-57 and the M-9-78 core are close; however, the Yarbo core samples show depletion relative to the other sites. This difference could be described by the possible fluid mixing and diagenetic scenarios discussed for the Yarbo samples; however, if the Yarbo core light end member δ^{18}O value recorded shallow meteoric phreatic δ^{18}O values, then the various effects on precipitation δ^{18}O chemistry must be considered. We have already discounted orographic, continental, and seasonal effects as contributors to Late Albian precipitation δ^{18}O chemistry along the eastern margin of the KWIS. In addition, the study sites were situated at approximately the same paleolatitude; therefore, Rayleigh distillation processes can be eliminated as a cause for the relative depletion between sites. In this case, the difference between sphaerosiderite δ^{18}O values and precipitation δ^{18}O estimates for the Yarbo core and the MC-57 and M-9-78 samples is best described by age differences between the two regions.

In the cross-section, the Yarbo core region is situated west of MC-57 and Ste. Rose du Lac, Manitoba, and therefore may represent deposition and soil formation along an easterly time transgressive surface during relative sea-level rise. We hypothesize that sedimentary geochemical processes recorded in the Swan River Fm of the Yarbo core may have been active prior to the Kiowa–Skull Creek highstand when isolated northern and southern arms of the KWIS merged (Kauffman, 1977). If correct, then the source of atmospheric vapour to the Yarbo region during sphaerosiderite formation would have been from an isolated northern arm of the KWIS. The source of water to this isolated northern arm was the Boreal Sea, which likely had relatively δ^{18}O depleted surface waters. This model can account for the relative depletion in sphaerosiderite δ^{18}O values between the Yarbo core and the MC-57 and M-9-78 samples.

5. Mid-Cretaceous Paleoclimatological Interpretations

The following points best summarize the sequence stratigraphic, palynologic, and soil micromorphologic investigations of Albian sphaerosiderites from the Swan River Fm in eastern Saskatchewan and western Manitoba:

1) Sphaerosiderite-bearing horizons in the Swan River Fm likely formed in the Late Albian in coastal lowland wetland soils. The sediments of the Swan River Fm are interpreted to have aggraded in fluvial and estuarine environments coincident with rising regional base levels associated with early transgression of the Kiowa–Skull Creek Marine Cycle in the Western Interior Seaway.
2) Soil micromorphologic characteristics and the presence of freshwater algal forms in the Swan River Fm indicate that most of the sphaerosiderites were formed in gleyed freshwater paleosols.
3) Assuming that model-generated temperatures for mid-Cretaceous North America are accurate, paleoprecipitation δ^{18}O values can be calculated from sphaerosiderite δ^{18}O values.

With these key points in mind, it is possible to begin unraveling the paleoclimatologic signal recorded in the sphaerosiderites. However, to interpret precipitation δ^{18}O values, the latitudinal (temperature), continental, altitudinal, seasonal, and amount effects on the δ^{18}O (Rozanski *et al.*, 1993) must be considered.

Since the samples are from alluvial-coastal plain depositional settings with no mountains along the KWIS cratonic margin (Witzke and Ludvigson, 1996), orography cannot be a control on sphaerosiderite δ^{18}O values. Furthermore, as all of the strata were deposited within about 200 km of the paleoshoreline (White *et al.*, in press), any continental effect is considered minimal. Palynological studies from sites bracketing the study area suggest that the role of seasonal temperature and evapotranspiration changes along the eastern margin of the KWIS was likely minor. In the Mattagami Formation, Ontario, vegetation existed under humid climates (Telford *et al.*, 1991), and Pierce (1961) suggested that lower Upper Cretaceous strata of Minnesota record a moist, warm temperate rain forest similar to the present-day Pacific Northwest. He concluded that precipitation rates were regular and high, fog was abundant, and that there was little difference between mean temperatures for the coldest and warmest months of the mid-Cretaceous year.

Modern latitudinal precipitation δ^{18}O distributions are best understood considering that the major water vapour source is the tropical ocean with poleward transport of the vapour connected to gradual rain-out, reduction of precipitable water in the atmosphere, and a depletion in the ^{18}O content of the remaining water (Rozanski *et al.*, 1993). However, the oceans may not be the major vapour source to land adjacent to large epicontinental water masses (Rozanski *et al.*, 1993), so Rayleigh distillation processes may not be entirely appropriate for understanding hydrologic budgets near epicontinental seas. Valdes *et al.* (1996) showed that warm moist air advection from the KWIS had an ameliorating effect on the North American climate. Ocean models indicate that southeastern KWIS surface water was derived from the subtropics (Poulsen, 1999), and a KWIS circulation model describes a north-flowing coastal jet along the eastern margin which drew Tethyan waters into the seaway (Slingerland *et al.*, 1996). In the early Turonian KWIS circulation model, steady-state salinities >36 practical salinity units were attained north of mid-Cretaceous Manitoba and Saskatchewan. These salinities are equivalent to ocean surface water $\delta^{18}O$ values >1‰ in the modern Atlantic and Pacific Oceans (Broecker, 1993). Furthermore, the results of modeling mid-Cretaceous mean annual wind fields over North America (early Turonian, Slingerland *et al.*, 1996; Cenomanian, Valdes *et al.*, 1996) suggest that easterly to southeasterly winds would have drawn moisture from the north-central KWIS toward the present-day Manitoba Escarpment. Therefore, if similar oceanic and atmospheric circulation patterns were established during the Late Albian, the north-central KWIS was the vapour source to the Late Albian Manitoba-Saskatchewan region. As discussed above, north-central KWIS surface waters were likely relatively enriched and cannot account for the depletion recorded in the Swan River Fm sphaerosiderite $\delta^{18}O$ values. If we assume the surface water $\delta^{18}O$ values were equal to zero, then we must account for processes that led to a 10‰ depletion in precipitation $\delta^{18}O$ values. Since the Boreal Sea $\delta^{18}O$ composition is uncertain (although we believe it was relatively depleted), it is not possible to establish a baseline for assessing precipitation depletion in the Yarbo core samples (assuming they record precipitation $\delta^{18}O$ values).

A relationship between modern precipitation amount and precipitation $\delta^{18}O$ values has been established (Dansgaard, 1964; Rozanski *et al.*, 1993; and others). For partly continental settings, Dansgaard (1964) reported $\delta^{18}O$ values of -2‰/100 mm/month. Accepting the arguments for atmospheric vapour sources to mid-Cretaceous Manitoba and Saskatchewan and using paleoprecipitation $\delta^{18}O$ estimates for MC-57 and M-9-78 samples and the modern partly continental amount-effect relationship, Late Albian precipitation rates in Manitoba and Saskatchewan may have attained values of ~6000 mm/year, or >200 inches/year. These values are more similar to modern annual tropical precipitation rates (Rozanski *et al.*, 1993), in this case occurring in the mid-Cretaceous high mid-latitudes, and support the notion of an enhanced atmospheric hydrologic cycle for the mid-Cretaceous greenhouse world (Barron *et al.*, 1989).

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Latitude-dependent Climatic Response to Milankovitch Orbital Forcing and its Expression in Cretaceous Rocks of the Northern Hemisphere

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Meyers, S.R. and Sageman, B.B. (2000): Latitude-dependent climatic response to Milankovitch orbital forcing and its expression in Cretaceous rocks of the northern hemisphere; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

1. Introduction

Quantitative analysis of Milankovitch orbital periodicities in the rock record has two fundamental applications. The first is improvement of chronostratigraphic resolution since orbitally forced patterns of sedimentation provide an internal chronometer that exceeds the resolution of any other relative or absolute dating method applicable to pre-Pleistocene sedimentary deposits. The second is improved understanding of the relationships that link orbitally forced variability of insolation to climate change, oceanographic change, and ultimately change in sedimentation to produce rhythmically bedded strata (Figure 1). Analysis of hemipelagic successions, which are among the best recorders of orbital forcing, offers an opportunity to examine the effect of these climatic changes on the different pathways of sedimentation that establish the climate-sedimentation linkage: 1) a detrital pathway (characterized by terrigenous components such as clays and terrestrial organic matter) sensitive to changes in precipitation and resultant terrigenous influx, and 2) a pelagic biogenic pathway (characterized by skeletal material and pelagic organic matter) sensitive to water column conditions that affect productivity (Figure 1). The accumulation of organic matter associated with the detrital pathway and pelgaic biogenic pathway is also sensitive to redox state within the water column and sediments (Figure 1). Because orbital forcing places testable constraints on the behavior of these two pathways, which may be related to latitudinal variation in the Milankovitch-forced insolation (Figure 1), a succession in which orbital parameters are quantified offers the possibility to deconvolve the relative roles of each. With the application of reasonable uniformitarian principles, the study of such strata provides evidence for reconstructing the behaviour of ancient climatic and oceanographic systems.

One of the key advantages to the study of orbitally influenced strata is the potential to place a stratigraphic sequence within a high-resolution quantifiable time series. This makes possible the calculation of accumulation rates for both detrital and biogenic components. We believe that application of this quantitative cyclostratigraphic approach in conjunction with organic and elemental geochemistry (Figure 1) and published paleontologic data sets will advance our knowledge of the climate-sedimentation linkage during the mid-Cretaceous greenhouse regime. In particular, this methodology will be applied to reconstruct biogeochemically significant processes such as the flux of organic matter to sediments resulting from increased primary productivity.

This approach is based on recent quantitative documentation of orbital signals in rhythmic limestone-marlstone facies of Cenomanian-Turonian (C-T) age in the central Western Interior using spectral techniques (Sageman *et al.*, 1997). The purpose of this study is to further test the Milankovitch model by investigating the three central questions (working hypotheses) resulting from earlier studies:

1) Does limestone-marlstone formation reflect climatic forcing of siliciclastic dilution, carbonate productivity, or a combination of both? If a combination, how is each process controlled, and how do they interact?
2) Does the unique pattern of bedding in central basin deposits reflect latitude-dependent forcing of different orbital parameters through different depositional pathways? Specifically, does obliquity dominate detrital flux through forcing of the higher latitude hydrologic cycle, and precession dominate biogenic flux (carbonate) through forcing of lower latitude surface water conditions?
3) How are the Milankovitch-scale variations expressed in limestone-marlstone facies influenced by longer-term changes in the ocean-climate system, such as the global carbon burial and ocean anoxic event termed OAE II? Can we detect feedback in the carbon cycle-climate relationship via changes in latitude-dependent orbital forcing (e.g. increase in organic carbon burial, decrease in $p\mathrm{CO}_2$, decrease in temperature, increase in precipitation, increase in dilution)?

2. Study Area

The Cretaceous Western Interior Seaway (KWIS) offers an ideal opportunity to investigate meridional variations in orbital insolation, greenhouse climate system

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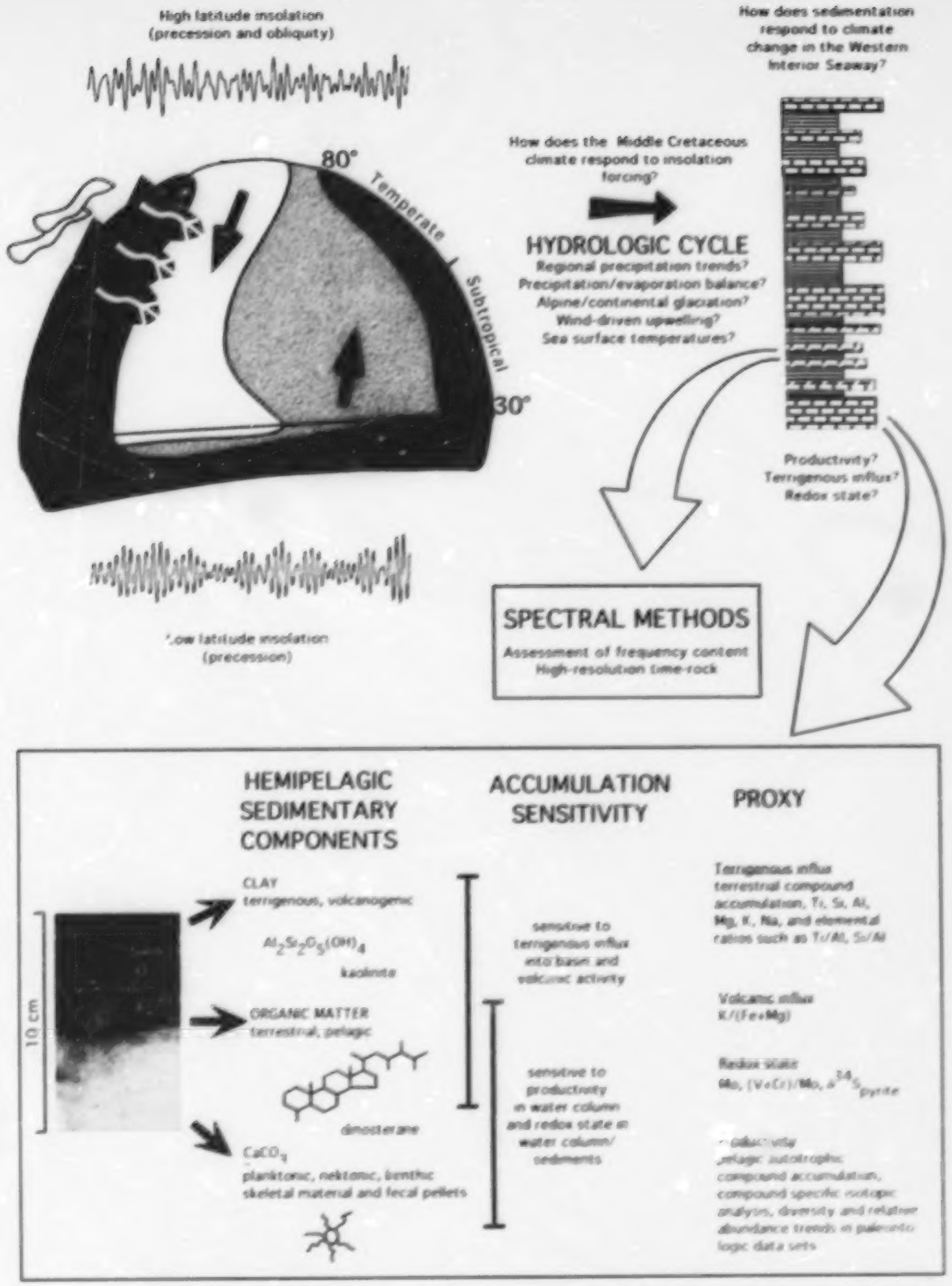
High latitude insolation (precession and obliquity)
80°
Temperate
Subtropical
30°
Low latitude insolation (precession)
How does the Middle Cretaceous climate respond to insolation forcing?
HYDROLOGIC CYCLE
Regional precipitation trends?
Precipitation/evaporation balance?
Alpine/continental glaciation?
Wind-driven upwelling?
Sea surface temperatures?
How does sedimentation respond to climate change in the Western Interior Seaway?
Productivity?
Terrigenous influx?
Redox state?
SPECTRAL METHODS
Assessment of frequency content
High-resolution time-rock
HEMIPELAGIC SEDIMENTARY COMPONENTS
ACCUMULATION SENSITIVITY
PROXY
10 cm
CLAY
terrigenous, volcanogenic
Al2Si2O5(OH)4
kaolinite
ORGANIC MATTER
terrestrial, pelagic
dinosterane
CaCO3
planktonic, nektonic, benthic skeletal material and fecal pellets
sensitive to terrigenous influx into basin and volcanic activity
sensitive to productivity in water column and redox state in water column/sediments
Terrigenous influx
terrestrial compound accumulation, Ti, Si, Al, Mg, K, Na, and elemental ratios such as Ti/Al, Si/Al
Volcanic influx
K/(Fe+Mg)
Redox state
Mo, (V+Cr)/Mo, δ34S pyrite
Productivity
pelagic autotrophic compound accumulation, compound specific isotopic analysis, diversity and relative abundance trends in paleontologic data sets

Figure 1 - Summary of research questions and analytical approach. Diagram of Cretaceous Western Interior Seaway displays: 1) hypothesized circulation and water masses (Slingerland et al., 1996), and 2) meridional variability in insolation, characterized by precession dominance in the low latitudes, with increasing obliquity influence in the high latitudes; insolation curves calculated for the last million years at 0° and 89° north, using the La90 (Laskar, 1990) orbital solution. The proposed effects of Milankovitch-forced insolation variability on the hydrologic cycle, and the methods used to assess the climate-sedimentation linkage are also shown.

response, and the resulting stratigraphic expression of Milankovitch periodicity. The Western Interior Basin has widespread distribution of rhythmically bedded, alternating clay-rich and carbonate-rich hemipelagic facies of Cenomanian-Turonian (C-T) age commonly interpreted to represent Milankovitch forcing. The meridional geometry of these deposits is represented by preserved C-T strata in cored boreholes from Canada to Mexico, and extends outside the basin to South America, making possible a high to low latitude survey (Figure 2). The chronostratigraphy and correlation potential for the C-T interval throughout this meridional extent is excellent based on molluscan and microfossil biostratigraphy (Cobban, 1984, 1985; Eicher and Diner, 1985; Kauffman *et al.*, 1998; Bralower and Bergen, 1998; Villamil and Arango, 1998), geochronology (Obradovich, 1993), and chemostratigraphy (Pratt, 1985; Schlanger *et al.*, 1987). In particular, the carbon isotopic excursion associated with the Ocean Anoxic Event II presents a unique opportunity for high-resolution correlation of the time series between sites.

Published spectral analysis of lithologic and geochemical time series (greyscale, total organic carbon, and carbonate) from a core of the rhythmic limestone-marlstone facies of the C-T interval in the central part of the basin (near Pueblo, Colorado) has provided statistical confirmation of Milankovitch periodicities (Sageman *et al.*, 1997, 1998). These time series display variations in spectral response suggesting that the different depositional pathways that delivered detrital material and carbonate to the sediment were controlled by different orbital forcing factors. This observation suggests a primary working hypothesis: climate-controlled variations in siliciclastic dilution and associated redox conditions were dominantly controlled by high-latitude obliquity whereas pelagic productivity (especially coccolithophores) was dominantly influenced by low-latitude precession. The application of a meridional analysis, in conjunction with a carefully chosen set of geochemical parameters which provide excellent proxies for changes in detrital sedimentation and primary production (Figure 1), spectral methods, and published paleontologic datasets, will allow a quantitative assessment of this hypothesis.

To test the hypotheses outlined above, three core sites were chosen in addition to the previously studied #1 Portland core from Colorado (Figure 2, core B) to complete a meridional transect. These include: 1) the Noranda Neely 16-21-34-27W3 core from Saskatchewan, Canada (Figure 2, core A) in which the C-T interval is represented by the Second White Specks Formation; 2) the Newton #1 from southwest Texas (Figure 2, core C) in which the C-T interval occurs within the Eagle Ford Formation; and 3) the Cocuyo core from the northern part of the middle Magdelena basin of Colombia (Figure 2, core D) that penetrates rhythmically bedded C-T facies of the La Luna Formation previously studied by Villamil (1996).

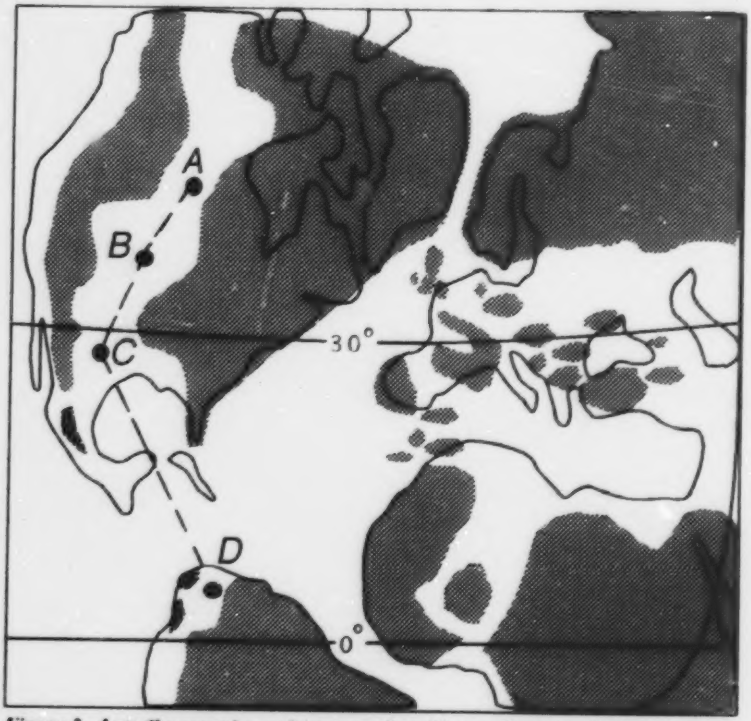

Figure 2 - Late Cenomanian paleogeography with sampling sites indicated (modified from Sageman, 1991).

3. Time Calibration

Assessment of the time-rock relationship in the C-T strata is facilitated by four phenomena (Figure 3): 1) the global $\delta^{13}C_{org}$ isotopic excursion associated with OAE II (Pratt, 1985; Schlanger *et al.*, 1987), 2) published ^{40}Ar-^{39}Ar radiometric dates from bentonites (Obradovich, 1993), 3) the existence of well defined biozones within and outside of the basin (Cobban, 1984, 1985; Eicher and Diner, 1985; Kauffman *et al.*, 1998; Bralower and Bergen, 1998; Villamil and Arango, 1998), and 4) the potential preservation of Milankovitch orbital periodicities within the strata as lithologic and/or geochemical signatures. First order sedimentation rates can be assessed by identification of the OAE II carbon isotope excursion at each study locality. Even in areas of the basin with few bentonites, time control can be "imported" using this isotope excursion. These estimates can then be refined using time series analysis techniques such as evolutionary spectral analysis and wavelet analysis, provided that orbital-scale periodicities are preserved in the strata in some fashion (i.e. in a geochemical or lithologic parameter). Using this methodology, high-resolution sedimentation rates will be developed at each study locality, and subsequently applied to the individual geochemical time series to assess accumulation.

4. Proxies

The multi-proxy approach implemented in this study includes bulk geochemical, elemental geochemical, organic geochemical, and paleontologic data sets. The method includes parameters to be utilized as proxies for pelagic productivity, redox state, terrigenous influx, and volcanogenic input (Figure 1). Together these data reflect the history of relative inputs from pelagic biogenic sources and terrestrial sources, and the perservational capacity of organic matter derived from these sources.

These analyses will be performed first on individual bedding couplets (or equivalent lithologic expressions, as may be defined by optical densitometry) to address the relative roles of dilution vs. productivity in couplet formation. Then they will be compared to results for couplets sampled prior to, within, and following the OAE II interval to evaluate the modulation of Milankovitch sedimentation by the oceanic anoxic event. Finally, they will be compared to results between the different sections in the paleolatitudinal transect to assess latitudinal variations in orbital forcing of sedimentation processes.

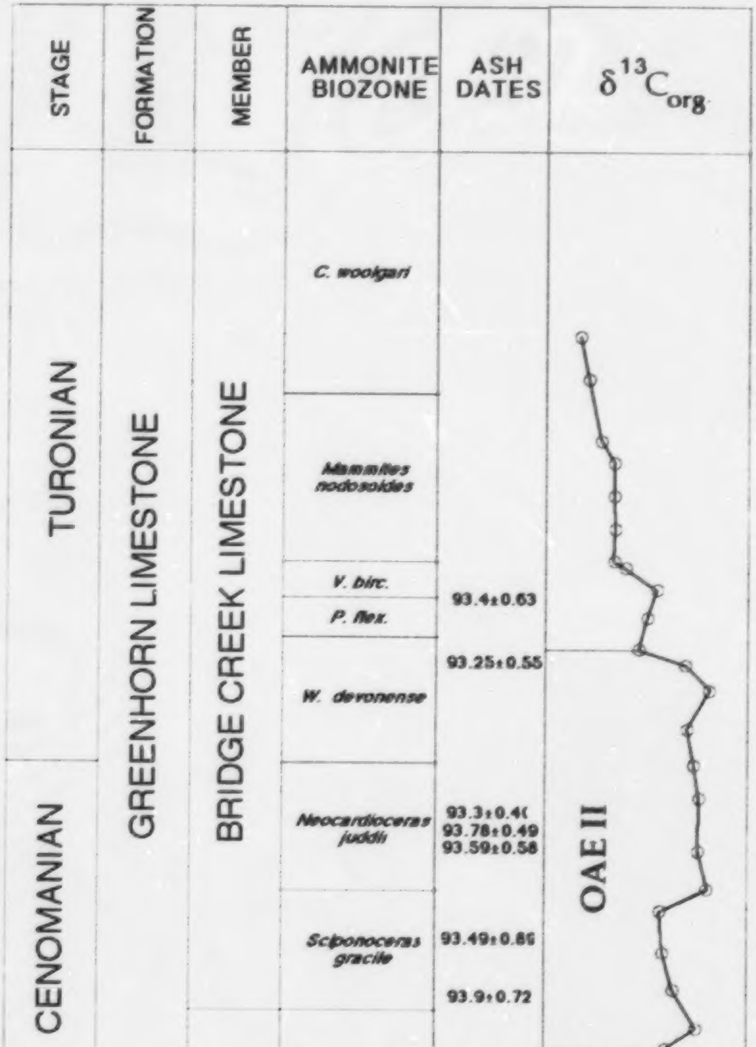

Figure 3 - Late Cenomanian–Early Turonian biozones (Kauffman et al., 1998), available radiometric dates (^{40}Ar-^{39}Ar method) (Obradovich, 1993), and the organic carbon isotopic excursion associated with OAE II, as expressed in Pueblo, Colorado (Pratt, 1985).

5. Current Status

This latitudinal survey of the mid-Cretaceous greenhouse regime is in its initial phase. The study has focused on central basin deposits (#1 Portland core) of the Bridge Creek Limestone Member (Meyers *et al.*, 1998, 1999), in which limestone-marlstone couplets are well expressed. High-resolution sedimentation rates have been developed for this core by applying evolutionary spectral analysis to an optical densitometry time series obtained from core photographs. The time-rock relationship developed in this fashion has been applied to compound abundances (determined by GC-MS analysis of lipid-extracted core samples) to assess their accumulation. The results have been compared to published paleontologic data sets (Leckie, 1985; Elder, 1985), and suggest changes in productivity on the Milankovitch and OAE II timescales (Meyers *et al.*, 1999). In addition to this work on the central basin deposits, the Second White Specks Formation (Noranda Neely core), drilled by IMC Kalium Colonsay near Saskatoon, Canada, has been photographed, described, and sampled at a resolution of 5 cm for future geochemical analyses.

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High-resolution Stratigraphy, Regional Correlation, and Report of Molluscan Faunas: Colorado Group (Cenomanian-Coniacian Interval, Late Cretaceous), East-central Saskatchewan

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Collom, C.J. (2000): High-resolution stratigraphy, regional correlation, and report of molluscan faunas: Colorado Group (Cenomanian-Coniacian interval, Late Cretaceous), east-central Saskatchewan; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

1. Introduction

This report presents data resulting from joint field research during 1992, 1994, and 1995. The multidisciplinary project, informally named the "Carrot River/Pasquia Hills Project" (CRPHP), was jointly sponsored by the Canadian Museum of Nature, Ottawa (S. Cumbaa, coordinator) and the Royal Saskatchewan Museum, Regina. Aspects of CRPHP research, mostly addressing vertebrate paleontology, have been previously presented in Cumbaa *et al.* (1992), Cumbaa and Tokaryk (1993), Tokaryk *et al.* (1997), Cumbaa *et al.* (1997), Cumbaa (1999), and Cumbaa and Tokaryk (1999). Future CRPHP research will focus on systematic description of the various marine fauna, such as elasmobranch and ray teeth (Cumbaa and Stewart), teleostid fish (Stewart), marine reptiles (Wu *et al.*, in review), and molluscs and invertebrate communities (Collom). The abundant inoceramid *Mytiloides labiatus*, not illustrated herein, is the focus of a forthcoming monographic study (Collom) that will compare populations of this cosmopolitan Turonian bivalve from each of the western Canadian provinces. All specimens illustrated herein are stored at the Royal Saskatchewan Museum (Regina), the Royal Tyrrell Museum of Palaeontology (Drumheller), and the Geological Survey of Canada (Vancouver).

2. Stratigraphic Framework

Fine-grained facies of the Colorado Group in eastern Alberta, Saskatchewan, and western Manitoba have received differing degrees of attention from mappers, stratigraphers, and paleontologists since the pioneering work of MacLean during the 1910s (Kirk, 1930; McLearn and Wickenden, 1936; Bannatyne, 1970). However, studies of the Cretaceous in Saskatchewan have been hindered by: 1) rare, widely separated outcrops; 2) horizontally bedded strata (reducing the potential for thick sections in river-cut valleys); and 3) the dominance of poorly consolidated fine-grained facies that are prone to slumping upon exposure. Nonetheless, biostratigraphically important molluscan macrofossils (ammonites and inoceramid bivalves) are surprisingly common and well preserved at Carrot River, Waskwei River, and Bainbridge River in Saskatchewan. These localities are the focus of CRPHP study to date. This report supplements and partially revises the landmark contribution of McNeil and Caldwell (1981).

Five northwesterly trending upland areas form the "Manitoba Escarpment" in eastern Saskatchewan and western Manitoba: Pembina Mountain, Riding Mountain, Duck Mountain, the Porcupine Hills, and the Pasquia Hills (McNeil and Caldwell, 1981, Figure 1). The northernmost of these, the Pasquia Hills, contains exposures suitable for detailed collecting and correlation. Due to the poorly indurated nature of the fine-grained marine facies, some of the exposures described herein may not be accessible in the near future. For example, the 25 m thick Bainbridge River exposure (Figure 4-1), discovered during the 1995 field research in the area north of Hudson Bay, Saskatchewan, was probably produced by valley wall collapse during the late 1980s or early 1990s. It is close to, and possibly developed from, Sections 21 (4.7 m thick) and/or 22 (2.45 m thick) in McNeil and Caldwell (1981). Additional information regarding the Pasquia Hills area may be obtained by contacting me at *cjcollom@mtroyal.ab.ca*.

a) Lithostratigraphy and Facies

Stratigraphic formations (Figure 2) addressed in this section were initially described by Kirk (1930) and Wickenden (1945), and refined by McNeil and Caldwell (1981). Detailed formal definitions are given in Glass (1990). The Cretaceous marine strata in Saskatchewan and Manitoba are part of the "eastern calcareous facies belt" (see Figure 3, Kauffman, 1977). In Alberta and western Saskatchewan, recognition of the lateral equivalents of the units discussed here is largely facilitated by molluscs, foraminifera, calcareous nannofossils, and marine and terrestrial palynomorphs (dinoflagellates, pollen). Also important are distinctive isochronous marker beds, such as bentonites (volcanic ashes) and rare coarse-grained sandstones and conglomerates. Correlation of the Colorado Group in eastern Saskatchewan westward to the Foothills region, based on facies patterns and on gamma- and resistivity-log responses, is undependable as few facies are common to both areas. High-quality biostratigraphic data are therefore essential for

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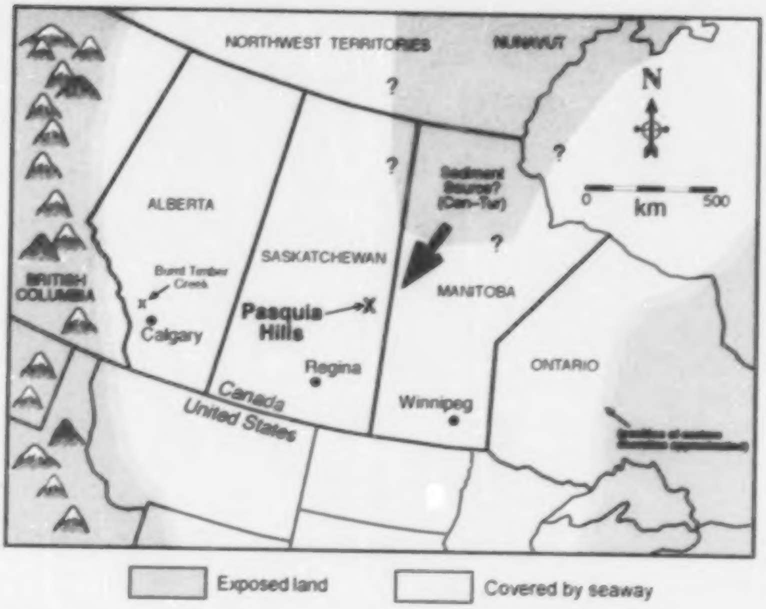

Figure 1 - Map of western and central Canada** (Mytiloides labiatus* ***Zone: Early Turonian), with reconstructed shorelines for the Cretaceous Western Interior Seaway, at the maximum sea-level transgression of the Greenhorn Cyclothem. Pasquia Hills and nearby Carrot River are denoted by 'X'. Large arrow indicates inferred provenance in Keewatin of siliciclastic sediments (siltstone and fine-grained sandstone) observed within the upper Ashville Formation at the Bainbridge River section. Given the considerable distance from eastern and western shorelines (~1000 km), large marine reptiles found at Carrot River (e.g. crocodiles) probably used coastal regions of this poorly documented land area for nesting and egg-laying. Migration into and emigration from the eastern portion of the seaway by species mentioned in this report may have occurred via the boreal "Hudson Arm" (connecting this region to West Greenland and northern Eurasia), rather than the "MacKenzie Arm" or Tethyan corridors.

constraining the ages of the Ashville, Favel, Morden, and Niobrara formations in the study area.

Ashville Formation

The Ashville Formation has four members (O-Y) in Saskatchewan: the Skull Creek, Newcastle, Westgate, and Belle Fourche. These are variably composed of organic-rich mudstone, siltstone, thin sandstones (quartzose), and concentrations of vertebrate and invertebrate skeletal material. Only the upper ~4.0 m of the Belle Fourche Member were observed at the Bainbridge River and Carrot River sections (Figure 3). The Belle Fourche Member is correlative to the lower Blackstone Formation (Sunkay Member) in the Rocky Mountain Foothills (Figure 2). In the subsurface of Alberta, these clastic facies are represented by offshore sandstones, the Barons Sandstone. At Bainbridge River, facies coeval to the Barons are represented by thin lenses and beds of silty to fine-grained sandstone (Figure 3) associated with accumulations of vertebrate skeletal debris, the Fish Scales Formation (Leckie *et al.*, 1992).

The boundary between the Ashville Formation and overlying Favel Formation represents a short hiatus, with silty, non-calcareous mudstones below and calcareous laminated mudstones above. The contact zone includes sparse, thin (<2 cm), silty to very fine-grained sandy beds deposited near the centre of the Western Interior Seaway during the Middle to Late Cenomanian transition. Neither the Cordilleran hinterland, some 1000 km to the west, nor the poorly known eastern shoreline, a comparable distance to the east, can be logically invoked as source regions. Because many of the quartz grains in these beds are angular to subrounded in shape, it is unlikely that they were transported such vast distances. I therefore suggest the existence of a more proximal sediment supply.

The Arctic region of Keewatin has been depicted as an exposed land area in most paleogeographic reconstructions of the Western Interior Seaway since the 1970s (Figure 1). This landmass separated the "MacKenzie Arm" of the seaway directly north of Alberta from the "Hudson Arm" of northwest Ontario and Hudson Bay. As a result of Pleistocene glacial activity, Phanerozoic strata on the Canadian Shield have been eroded away. If there was an upland during the Cretaceous flooding of North America, then sediments would have been transported from it to the seaway by normal fluvial processes. The Keewatin landmass is envisioned as the provenance for siliciclastics in the upper Ashville Formation at the Bainbridge River Section (middle Colorado Group). Marine facies in the Sverdrup Basin correlative with the Ashville and Favel formations (Christopher Formation and Hassel Formation: MacRae, 1992; Nuñez-Betelu, 1994) also contain anomalous quartz-rich sands that thicken towards Keewatin. As with the much thinner siltstones and sandstones in Saskatchewan and Manitoba, the Sverdrup Basin clastics were most likely derived from the otherwise unknown landmass between the Hudson and MacKenzie arms.

In the Crowsnest Pass area of southern Alberta, at the contact of the Blairmore and Alberta groups, >100 m of volcaniclastic rock of Early Cenomanian age are present and are thought to be coeval to the Fish Scales Formation, an easily recognized gamma-log marker in subsurface wireline data (Leckie *et al.*, 1992). Massive concretions up to 1.5 m in diameter and consisting

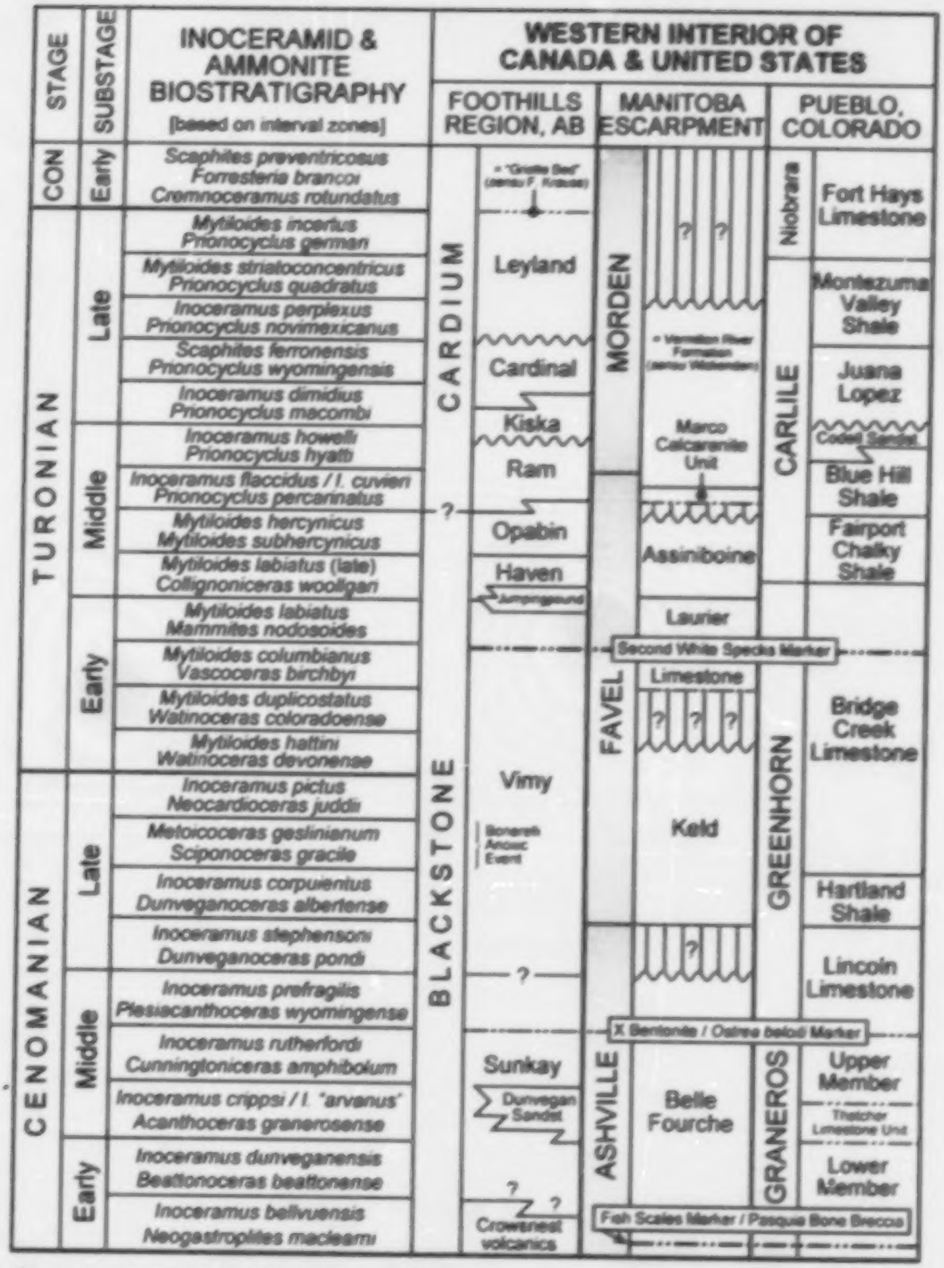

Figure 2 - Biostratigraphy and lithostratigraphy for the Early Cenomanian to Early Coniacian interval (mid- to Late Cretaceous), Western Interior of Canada and the United States. Members of the Blackstone Formation from Stott (1961), based on the newly designated WCSB reference section at Burnt Timber Creek, Alberta (see Figure 4-2). Vertical lines indicate disconformities and depositional lacunas. Contemporary ammonite and inoceramid-based interval zones modified from Cobban and Scott (1972) to accommodate new information (e.g. Collom, 1991; Kirkland, 1996). The *Sciponoceras gracile/Metoicoceras geslinianum* ***Zone represents a globally recognized anoxic interval ("Bonarelli Event"), equal to the Keld Member throughout the Manitoba Escarpment (marker beds B3 to B6, Figure 3). Both the*** *I. pictus* ***and*** *M. labiatus* ***zones are associated with the*** *Hedbergella loetterlei* ***Assemblage Zone (foraminifera), which straddles the Cenomanian-Turonian boundary. Disconformity within the Keld Member not well constrained, based on the absence of*** *M. duplicostatus* ***and*** *W. coloradoense* ***at all sections collected. The Laurier Limestone Beds (Keld Member, Early Turonian) represent the highest relative sea level of the Phanerozoic. Pueblo, Colorado section designated by Pratt*** *et al.* ***(1985) as the Western Interior reference section for the Cenomanian and Turonian stages, and the GSSP (Global Boundary Stratotype Section and Point) for the base of the Turonian (Bengtson, 1996).***

almost entirely of calcite-cemented teleost bones and selachian teeth were found by the CRPHP in the Pasquia Hills at a stratigraphic level comparable to the Fish Scales, in the upper part of the Ashville Formation (Figures 4 and 5, in Cumbaa and Tokaryk, 1999). This remarkable bioconglomeratic unit is herein named the Pasquia Bone Breccia (PBB).

Debate continues regarding the origin of the Fish Scales beds (Leckie *et al.*, 1992; Bloch *et al.*, 1993). Most investigators agree that one or more volcanically driven mass mortalities, primarily affecting fish, sharks, and certain plankton over a short time span, combined with sediment starvation resulting from sea-level rise, are the main causal mechanisms. The role of the Crowsnest Volcanics in formation of the Fish Scales Marker(s) is not established, but available biostratigraphy and geochronology support their penecontemporaneous age.

An as yet unnamed regressive-transgressive sequence in the lower Blackstone Formation (within the Sunkay Member) represents approximately the same stratigraphic horizon as the middle of the Belle Fourche Member. In northern Alberta, the zones of *I. dunveganensis* and *I. crippsi* correspond to the Shaftesbury Formation and Dunvegan Formation, situated between the Fish Scales and the "X Bentonite" markers (Figure 3). *Cunningtoniceras* sp. has been collected near the X Bentonite level at Burnt Timber Creek (Figure 4-2), but *Cunningtoniceras* or *Dunveganoceras* have yet to be found in Saskatchewan. Available data suggest the sandstone unit in the Sunkay Member is coeval to the Dunvegan Formation, and these in turn are correlative to <2.0 m of fine-grained sediment in the Pasquia Hills. Until additional evidence is found, it is concluded that a major progradation of the western shoreline of the WCSB occurred during the early Middle Cenomanian (*I. crippsi/A. granerosense* Zone) that is not easily recognized in the Pasquia Hills, and a hiatus is present at the Ashville-Favel formational contact (*I. stephensoni/D. pondi* Zone: early Late Cenomanian) that has no apparent analog in Alberta.

Biota

The relatively thin exposure (<1.5 m±) of the uppermost Ashville at the DH-3 site on Carrot River has yielded well preserved pneumatic bones representative of the oldest avifauna known from the Western Interior (Cumbaa and Tokaryk, 1999). No age-diagnostic molluscs were collected at this site, but marine dinoflagellates from near DH-3 corroborate a Middle to Late Cenomanian age for the lowest exposed strata on Carrot River (D. Jarzen, pers. comm., 1996). Nicholls *et al.* (1990), describing remains of marine protostegid turtles, provisionally assigned a Coniacian age to isolated outcrops of the upper Belle Fourche Member (e.g. near DH-3, see Figure 3 in Cumbaa and Tokaryk, 1999). Subsequent identification of the diagnostic foraminifera *Verneuilinoides perplexus* (D. McNeil, pers. comm., 1992) and marine dinoflagellates (D. Jarzen, pers. comm., 1994) from this level provides a reliable Middle Cenomanian age for this lower bioclastic bone unit. These correlations suggest that this concretionary bone layer (SMNH 63E03-0001 in Cumbaa and Tokaryk, 1999) may be laterally equivalent to the PBB (at SMNH 63E09-0003), although few, if any, upper Ashville exposures are present in the 115 km distance between Carrot and Bainbridge rivers.

Favel Formation

The Favel Formation consists of two members: the Keld and overlying Assiniboine (Figure 3). The formation is composed predominantly of laminated, dark grey to black, marine mudstone and ten bentonite beds, ranging in thickness from <1.0 cm to ~10 cm. The thickest bentonite, herein referred to as B7 (numbering consecutively from the contact with the Belle Fourche below), occurs *between* the two prominent, argillaceous limestone layers of the Laurier Limestone Beds regional marker unit (McNeil and Caldwell, 1981). The Laurier Limestone Beds, at the top of the Keld Member, are ~20 to 30 cm thick and are the only well indurated sedimentary unit within the Favel Formation in the Pasquia Hills.

The Favel Formation is exposed at each of the four sections investigated (the base of the Laurier Limestone Beds is used as datum for correlation in Figure 3), but the lower and upper contacts were observed only at the Bainbridge River locality. This is the most complete section of the Favel Formation in the Pasquia Hills and perhaps in the entire Manitoba Escarpment. The Keld Member is almost entirely Late Cenomanian (*Inoceramus corpulentus, I. pictus* zones) in age, whereas the Assiniboine is Middle Turonian (*Mytiloides hercynicus* Zone). The cosmopolitan guide fossil *Watinoceras* is apparently absent in the Favel Formation. This is the index ammonite for recognition of the basal Turonian (*W. devonense*) in Western Canada.

The most spectacular vertebrate found by CRPHP investigators is a 6.5 m long specimen of the crocodylomorph *Terminonaris* (identified as *Teleorhinus* in previous reports, but this is a preoccupied name) on Carrot River. Bones of this 95 percent complete individual were collected from marine mudstones immediately below the Laurier Limestone Beds (Figure 3). This large marine reptile is, therefore, most likely of Early Turonian age (*Watinoceras* spp. Zone). Its excavation was started by Tokaryk in 1991. A complete description of the reptile is forthcoming (Wu *et al.*, in review). The skull is nearly 1.25 m in length and boasts at least two re-healed injuries presumably from duels with other members of its species. The death of this otherwise healthy individual probably resulted from an attack by another *Terminonaris* (Tokaryk, pers. comm., 1994). Despite abundant shark teeth within and immediately adjacent to the Laurier Limestone Beds at both Carrot River localities, the *Terminonaris* shows little evidence of post-mortem scavenging. The articulated nature of the skeleton attests to the low oxygen and low current

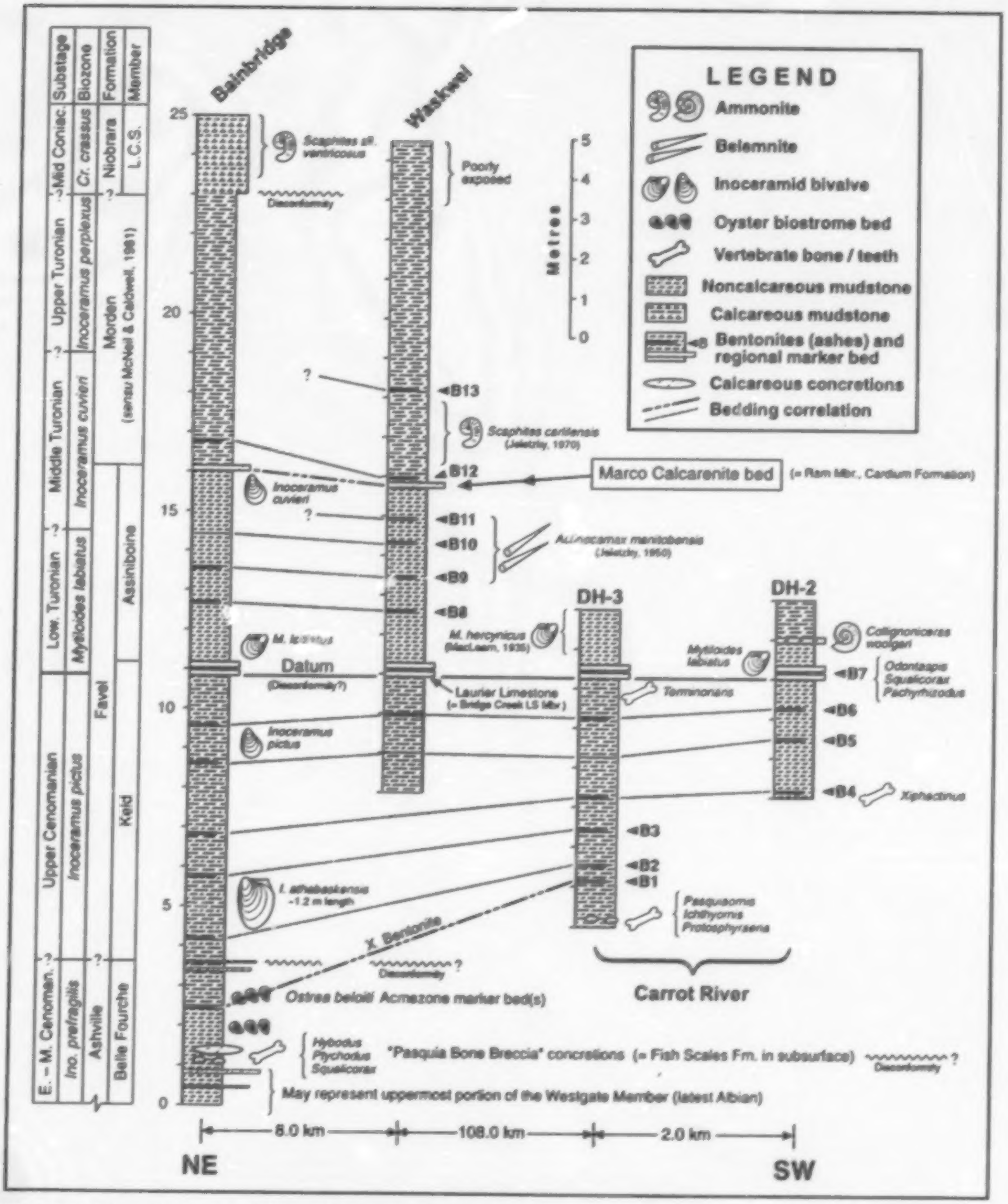

Figure 3 - High-resolution correlation of the four surface outcrops described in this report. Datum is the regionally persistent limestone bed couplet of the Laurier Limestone Beds (Keld Member), encompassing marker bentonite B7 (~10 cm thick). Stratigraphic occurrences of important vertebrate and molluscan fossils are indicated. The Bainbridge River section (Cumbaa* et al., *1997) is designated as the reference section for the Favel Formation in the Pasquia Hills region. The Pasquia Bone Breccia Unit (PBB) has only been confirmed at Bainbridge River, the northeastern part of the study area, but may be represented by a thinner, concretionary bioclastic layer at the DH-3 section. X Bentonite and* Ostrea beloiti *biostrome, event beds having been traced throughout the Western Interior, were initially correlated across the Manitoba Escarpment by McNeil and Caldwell (1981). Not depicted are the decimetre-thick bedding rhythms representing the precessional cycle (~21 Kyr), best developed in the Favel and Niobrara formations.

energy conditions on the Early and Middle Turonian seafloor.

A notable exception to this general condition of quiet water deposition is the Marco Calcarenite in the uppermost Favel (McNeil and Caldwell, 1981, p36). This unit is made up of micritic, calcite-cemented, fine-grained quartz sandstone and siltstone. Bioclasts are predominantly fragmented cryptodontid bivalves (*I. cuvieri* Sowerby; Middle Turonian). This marker has been recognized at the Bainbridge and Waskwei sections (Figure 4-4). At the DH-2 locality (Carrot River), a ~10 cm thick argillaceous limestone bed 1.0 m above the base of the Laurier Limestone Beds contains the early Middle Turonian guide fossil *Collignoniceras woollgari* (Mantell). It probably does not represent the Marco Calcarenite (Figures 2 and 3).

Biota

Case *et al.* (1990) reported a Coniacian age for the elasmobranch fauna of the Laurier Limestone Beds and adjacent facies of the middle Favel. As implied by Cumbaa and Tokaryk (1999, p60), this age assignment is now considered to be inaccurate as *in situ* specimens of inoceramid bivalves and key ammonite species, present at both the Western Interior reference section (Pueblo) and throughout western Europe (Kauffman, 1977), were collected from these strata during CRPHP field work. The presence of the cryptodont *Inoceramus prefragilis* Stephenson and *I. athabaskensis* McLearn in the basal 2 m of the Keld Member restricts the oldest portion of the Favel Formation to the Middle Cenomanian. Numerous specimens of *Mytiloides labiatus* (Schlotheim) with disarticulated and paired valves have been recovered from the Laurier Limestone Beds and the lowest part of the Assiniboine Member, indicating that the Cenomanian-Turonian boundary is within otherwise homogenous calcareous mudstones of the upper Keld Member (the *Whiteinella aprica* Subzone). Therefore, the uppermost portion of the Keld Member is not younger than late Early Turonian.

Upper Cenomanian basinal mudstones worldwide record an unfossiliferous interval of dramatically heightened organic carbon storage, the Bonarelli Global Anoxic Event (GAE) (Jenkyns *et al.*, 1994). Although causal explanations vary, in several Euramerican localities this event appears to have either initiated, or was associated with, accelerated background extinction rates of benthic and pelagic marine organisms. In the WCSB, the Bonarelli GAE is recognized within the Vimy Member, Blackstone Formation (Alberta), and the Keld Member in Saskatchewan. No obvious mortality events are known from these intervals in Western Canada, but there are few invertebrates within certain 5 to 10 m thick portions of the Blackstone Formation that are interpreted to have been deposited during this anoxic event. Dark grey to black shales with potentially high TOC content (>5.0 wt%) in the lower Vimy Member may be evidence of the Bonarelli GAE. Geochemical samples of the Favel Formation were not collected, but these may be forthcoming from other workers in the Pasquia Hills (e.g. Schröder-Adams *et al.*, 1999).

Morden Formation

The dark grey to black, laminated, generally non-calcareous mudstones of the Morden Formation are one of the more distinctive facies in the Manitoba Escarpment. Resting unconformably(?) on the Marco Calcarenite (Favel Formation), these middle and upper Turonian fine-grained sediments display little bioturbation (rare *Chondrites* and *Planolites*), and contain far fewer inoceramid bivalves and ammonites than the older Favel Formation and younger Niobrara Formation calcareous facies.

Biota

Characterization of the Morden Formation is best accomplished by foraminifera and calcareous nannofossils, which are relatively plentiful. McNeil and Caldwell (1981) documented *Pseudoclavulina* sp., *Trochammina ribstonensis* Wickenden, and *Hedbergella loetterlei* (Nauss), indicating a Middle Turonian age. The ammonite *Prionocyclus hyatti* (Stanton) was reported by Jeletzky (1970) but its locality was not indicated and efforts towards finding this specimen within the collections of the Geological Survey of Canada in Ottawa have not been successful. This biostratigraphic tie-point, therefore, remains unconfirmed. Erosional removal or non-deposition of facies recording the Turonian-Coniacian boundary make it difficult to determine the youngest age for the Morden Formation, but it may be as high as the middle Late Turonian (e.g. *P. wyomingensis/S. ferronensis* Zone).

Niobrara Formation

The Niobrara Formation (Vermilion River Formation in Kirk, 1930) has two informal members in the Manitoba Escarpment region, the Calcareous Shale unit ("Lower Chalk Speckled Member" in McNeil and Caldwell, 1981, Figure 44) and the overlying Chalky unit ("Upper Chalky Member" in McNeil and Caldwell, 1981, Figure 44). As with the older Favel Formation, the facies of the Niobrara Formation are light to dark grey, laminated calcareous mudstone to marlstone. The poorly accessible cliff exposure at Bainbridge River is the single locality at which this formation crops out. A float specimen of *Scaphites* aff. *ventricosus* Meek and Hayden (Figure 6-1) was found not far downstream, indicating that the upper <2.0 m of exposed strata (Calcareous Shale Unit) are at least Middle Coniacian (*Cremnoceramus crassus* Zone, Figure 3).

b) Regional Correlation

The most comprehensive description and intra-regional correlation of facies along the Manitoba Escarpment is McNeil and Caldwell (1981). More than 100 sections were sampled for benthic and planktonic foraminifera,

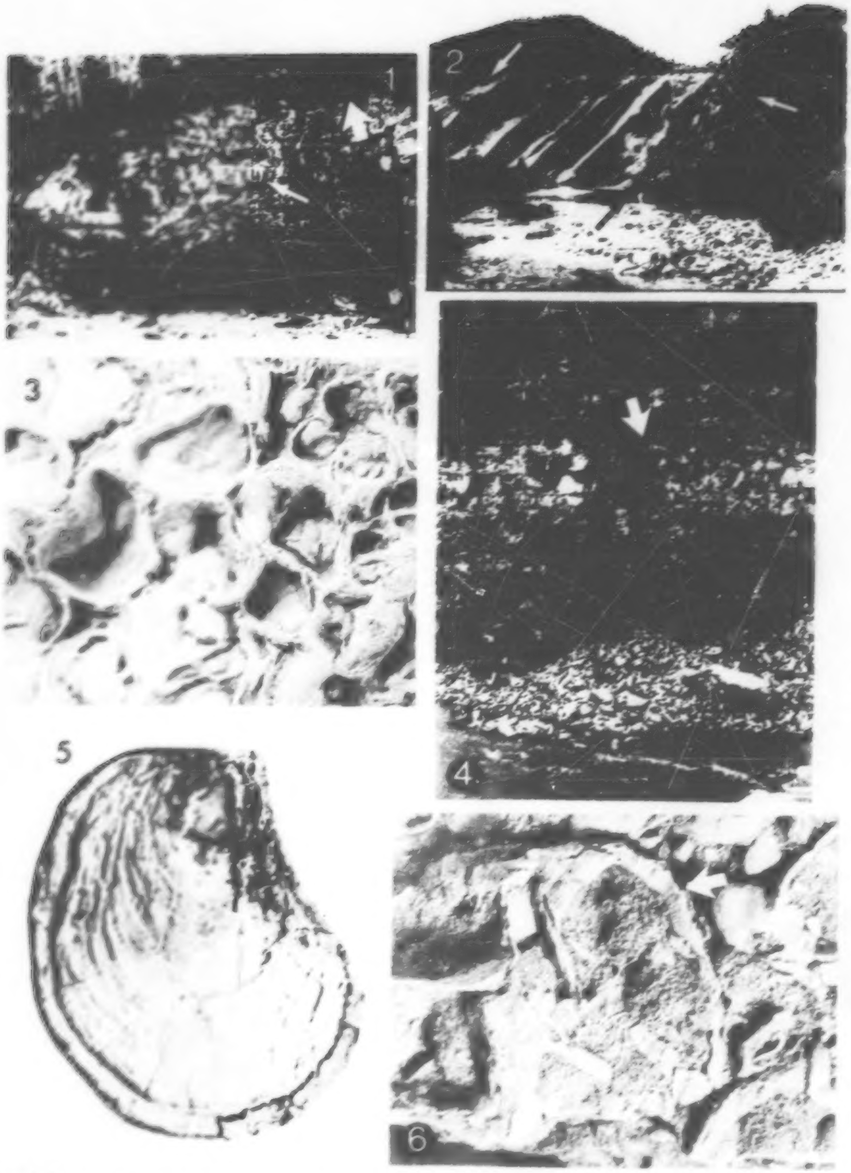

Figure 4 - (1) The highly condensed Bainbridge River section, representing fine-grained marine facies from the latest Albian?/earliest Cenomanian to Middle? Coniacian (~15 Myr in 25 m of strata); smaller arrow points to person for scale; (2) Sunkay Member, Blackstone Formation at Burnt Timber Creek, Alberta: coeval to Belle Fourche Member and lower Keld Member in Saskatchewan, note four consecutive parasequences (in shadows): black arrow to person (for scale), white arrow on right at position of 3rd-order sequence boundary capping shallowing-upwards interval: white arrow at left denotes position of the X Bentonite (Middle Cenomanian);(3) *Pseudoperna bentonensis* Logan - TMP 98.32.1 (x1.16), coquina slab of inter-cemented individuals, representing more than two generations of encrustation: Favel Formation, Bainbridge River; (4) Waskwei River section, containing upper Keld Member to upper? Morden Formation strata: debris fan at base of exposure has produced abundant vertebrates (shark teeth, bony fish, marine turtle), arrow indicates the Favel-Morden formational contact (person at lower left for scale);(5) *Inoceramus prefragilis* Stephenson (x0.77), lateral view of right valve (not collected): note preservation of original prismatic shell material: upper Belle Fourche Member, Bainbridge River; and (6) *Ostrea beloiti* Logan - TMP 98.32.2 (x0.96), view of numerous closely packed individuals in various states of disarticulation (arrow to near-complete left valve: note anachomata along ventral margin): upper Belle Fourche Member, Bainbridge River.

from the Skull Creek Member, Ashville Formation (Late Albian, *Haplophragmoides gigas*) to the Odanah Member, Pierre Formation (Late Campanian, *Haplophragmoides fraseri* Zone). Ten foraminifera-based zones were recognized and defined for this ~30 Myr interval. No advances were made, however, for co-occurring molluscan biozones. These were partially reported by Jeletzky (1970), although an investigation of Colorado Group macrofauna from the Manitoba Escarpment comparable in scope to McNeil and Caldwell's foraminiferal study is still lacking. Gill and Cobban (1965) reported on the ammonites and associated macroinvertebrates of the Colorado Group at nearby Pembina Mountain, North Dakota. Combined with later contributions (e.g. Obradovich and Cobban, 1975), no fewer than 40 zones, based on eight well documented ammonite lineages, have been established for the same time interval, with an average zone duration of <400 Ka.

Upon recognition of the established Western Interior molluscan biozones, and their corroboration with contemporary microfossils (foraminifera, dinoflagellates, calcareous nannofossils, and terrestrial palynomorphs), well guided observations can be made regarding depositional rates in different regions of the Cretaceous seaway. The Blackstone Formation of Alberta is coeval to the Belle Fourche, Keld, and Assiniboine members, as demonstrated by the equivalence of their macroinvertebrate faunas. At Bainbridge River, the thickest and most complete section of this interval in the Pasquia Hills, the Favel Formation is ~12.5 m thick (Figure 3). This is half the height of the Bainbridge exposure (25 m), which, in addition to the Favel, includes the uppermost part of the Ashville Formation, the Morden Formation, and possibly a portion of the "Lower Chalk Speckled" unit of the Niobrara Formation. Comparisons with Western Interior geochronology (Obradovich, 1993) indicate that nearly 15 million years are represented by this relatively thin interval. In the Foothills region of Alberta, the Bainbridge River equivalents include the Blackstone Formation (four members), Cardium Formation (five members), and at least the lower two members of the Wapiabi Formation (Muskiki and Marshybank)(Figure 2). Their total thickness is considerably greater than their counterparts in the east.

Of the many exposures of the Alberta Group (Blackstone, Cardium, Wapiabi), perhaps the most complete is at Burnt Timber Creek, northwest of Calgary. Here the marine and nearshore strata equivalent to those in the Bainbridge River section crop out in an essentially continuous river-cut exposure, and are approximately 1200 m thick. Thus, for every 1.0 m of deposition in Alberta, a scant ~2.0 cm accumulated on the shallow eastern platform of the WCSB. Furthermore, a composite section of the thickest Blackstone Formation (at Thistle Creek, Alberta), Cardium Formation (at Ram River, Alberta), and Wapiabi Formation (at Thistle Creek, Alberta) exposures would be ~1550 m thick (Stott, 1963; Collom, unpubl. data). The so-called foredeep, resulting from Sevier/Cordilleran overthrusting associated with terrane accretion along the western margin of North America, accounts for the considerably greater accommodation space in Alberta and British Columbia. These relationships bring to light the extreme condensation and sediment starvation that persisted in the eastern basin during the Late Cretaceous.

c) Correlation with Pueblo Reference Section

The above described Cenomanian and Turonian zones, illustrated in Figure 2, are known to a greater level of stratigraphic resolution than any other of Cretaceous age in North America. Research at Rock Canyon Anticline, south-central Colorado by the University of Colorado, Boulder campus (primarily graduate students of Erle Kauffman) has precisely constrained the biozone contacts of *Inoceramus pictus*, *Mytiloides hattini*, and *M. labiatus* to individual limestone beds within the Hartland and Bridge Creek members of the Greenhorn Formation (Elder, 1987; Kirkland, 1990; Harries, 1993). The bluffs and railroad cuts at Pueblo Reservoir, Colorado, were chosen as the reference section for the Cenomanian and Turonian stages in North America (Pratt *et al.*, 1985). This site will be referred to as the "WIRS", or Western Interior Reference Section.

The Second International Symposium on Cretaceous Stage Boundaries (Brussels, Belgium, Sept. 1995) went a step further by recommending that Pueblo be designated the international GSSP for the base of the Turonian (Bengtson *et al.*, 1996). Although the invertebrate fauna from the WIRS have more Tethyan and Euramerican affinities than Canadian equivalents with more Boreal and Indo-Pacific elements, the biostratigraphically important ammonite families and epifaunal bivalves are present in most Late Cretaceous marine realms (Kauffman, 1975). Comparisons between the WCSB and the Colorado-Kansas region were initially made by McNeil and Caldwell (1981, Figure 44) and McNeil (1984, Figure 13). Adjustments to those schemes are presented herein.

The uppermost Belle Fourche beds at Bainbridge and Carrot rivers are most likely Middle Cenomanian (*I. prefragilis/V. perplexus* Zone), and are correlative with the Sunkay Member of the Blackstone Formation in Alberta (Figure 2). This silty mudstone, above the Dunvegan Formation deltaic deposits of the Peace River Arch region, is coeval with the lowermost Kaskapau Formation. Presence of the widespread *O. beloiti/* X Bentonite marker beds (Middle Cenomanian) allow comparison with the upper Graneros Formation and lower Lincoln Member of the Greenhorn Formation in Colorado. The Ashville-Favel contact is traceable into the lower part of the Vimy Member (*I. stephensoni* Zone/*C. simplex* Subzone), which is essentially the same level as the base of the Hartland Member at the WIRS. The second zone of the Late Cenomanian (*D. albertense* Zone) contains both *I. corpulentus* McLearn and *I. flavus* Sornay, but the former species is more abundant in the WCSB.

The precise stratigraphic position of the Cenomanian-Turonian stage boundary (C-T) is not known for the

Manitoba Escarpment and is only approximated in the Rocky Mountain Foothills within the well studied Blackstone Formation. McNeil and Caldwell (1981, Figure 31) placed the C-T boundary a few metres above the base of the Keld Member, based largely upon the diagnostic foraminifera *Clavihedbergella simplex* and inferences "from common associates of zonal indices." As such, most of the Keld Member is Turonian. CRPHP collections indicate that there are no *M. labiatus* (late Early Turonian) from below the Laurier Limestone Beds, but there may be an earliest Turonian fauna within the upper part of the Keld Member. In contrast, the C-T boundary is restricted to a level fewer than 10 cm above marker limestone bed #86 (LS-7 of Elder, 1987) of the Bridge Creek Member, Greenhorn Formation, at the WIRS (Figure 5-5). This precisely defined, isochronous boundary is defined by the First Appearance Datum (FAD) of *M. hattini* and *Watinoceras* spp. Neither fossil has been found in the Pasquia Hills, suggesting that there may be a hiatus associated with the basal contact of the Laurier Limestone Beds.

A Late Cenomanian age for most of the Keld Member is confirmed by the presence of the cryptodont *Inoceramus athabaskensis* near the base and *I. pictus* near the top of the calcareous mudstone. *Inoceramus pictus* Sowerby is common within the lower six limestone and shale beds of the Bridge Creek Member at the WIRS. Peak transgression of the Greenhorn Cyclothem (2nd order sequence) during the Early Turonian facilitated the deposition of bedded limestone farther north than at any other time during the ~40 million year history of the Cretaceous seaway in North America. Along the Manitoba Escarpment this carbonate depositional episode is reflected in the Laurier Limestone Beds of the Keld Member. Calcareous concretion horizons within the upper half of the Vimy Member, Blackstone Formation, are a western equivalent of the Laurier Limestone Beds, as is the Bridge Creek Member (Figure 2). Nearly all continents with Turonian-age marine strata record moderately to very fossiliferous, carbonate-dominated beds during *Watinoceras* to *Mammites* time (~93 Ma BP).

The Assiniboine Member of the Favel Formation (Middle Turonian: *M. hercynicus* Zone) appears to be correlative with the Haven and Opabin members of the Blackstone Formation, although the silty and sandy facies of the Haven is not represented in Saskatchewan. The base of the Assiniboine Member is at the approximate level of the Greenhorn-Carlile contact (base of Fairport Member). The Marco Calcarenite, capping bed of the Favel Formation, shares faunal similarities with the Blue Hill Member of the Carlile Formation at the Pueblo WIRS, as both contain *I. cuvieri*. The relationship of the Marco Calcarenite to the Blackstone-Cardium transition is less clearly understood. The Marco Calcarenite may contain elements of the *I. howelli/P. hyatti* Zone (latest Middle Turonian), and therefore be partially correlative with the Ram Member (Cardium Formation) and Codell Member (Carlile Formation). These sandstone-dominated regressive units both have transitional, diachronous basal contacts and relatively sharp upper contacts. The Ram and Codell (and Marco Calcarenite?) appear to record a major shoreline progradational event that affected the entire Western Interior Seaway and was therefore probably not a reflection of local tectonism.

The Morden Formation was correlated by McNeil and Caldwell (1981) with the Blue Hill Member of the Carlile Formation based on *Heterohelix* cf. *reussi* (foraminifera) and *Prionocyclus hyatti*. This collignonicerid ammonite ranges up into the Codell Member of the WIRS, but only overlaps with the heteromorph *Scaphites carlilensis* Morrow in the lower half of the *I. howelli* Zone. It occurs with *I. costellatus* and *I. securiformis* in the Denver Basin, Colorado. Jeletzky (1970, Plate 26, Figures 7a and 7b) illustrated a *S. carlilensis* from the Morden Formation in Manitoba. No scaphitids have been collected from below the Niobrara Formation in the study area, but the relative position of Jeletzky's specimen is shown in the Waskwei River section in Figure 3. Nevertheless, the Morden Shale likely represents deposition into the Late Turonian to at least the *I. perplexus* Zone. Late Turonian representatives of the Carlile Formation (Juana Lopez and Montezuma Valley members) are well known (Collom, unpubl. data), and are correlative of the Cardinal Sandstone and lower Leyland Shale in Alberta (see Hall *et al.*, 1994). It seems that this *M. incertus* Zone is missing in the Pasquia Hills, but, is represented by a significant lacuna between the Morden Formation and the overlying Niobrara Formation. No macrofauna of certain early Coniacian affinities (e.g. *Cremnoceramus deformis* Zone) are known from Saskatchewan, but evidence is beginning to accumulate for the identification of Middle Coniacian strata (*C. crassus* Zone at the location shown in Figure 6-1).

3. Sequence Biostratigraphy

Establishment of regionally correlative Cretaceous molluscan biozones in marine successions of the Western Interior began in both Canada (McLearn, 1920) and the United States (Cobban, 1951) early in the 20th century. Concepts and applications of these zones, however, have changed considerably. The biozones used herein are *interval* zones (North American Commission on Stratigraphic Nomenclature, 1983, see Article 50), based on the first appearance datum (FAD) of the name-bearing taxa. High-resolution correlation of the fine-grained facies of the Colorado Group in Saskatchewan and Manitoba with the sandier and thicker successions in Alberta are lacking, but comparisons have been made (McNeil and Caldwell, 1981) based on micro- and macrofaunal occurrences. In terms of sequence stratigraphy, no fewer than four sequence boundaries (third-order level) are present. These are at the base of the Favel Formation, the base of the Marco Calcarenite, the base of the Morden Formation, and the base of the Niobrara Formation. A possible fifth unconformity may exist at or near the base of the Laurier Limestone Beds (Keld Member).

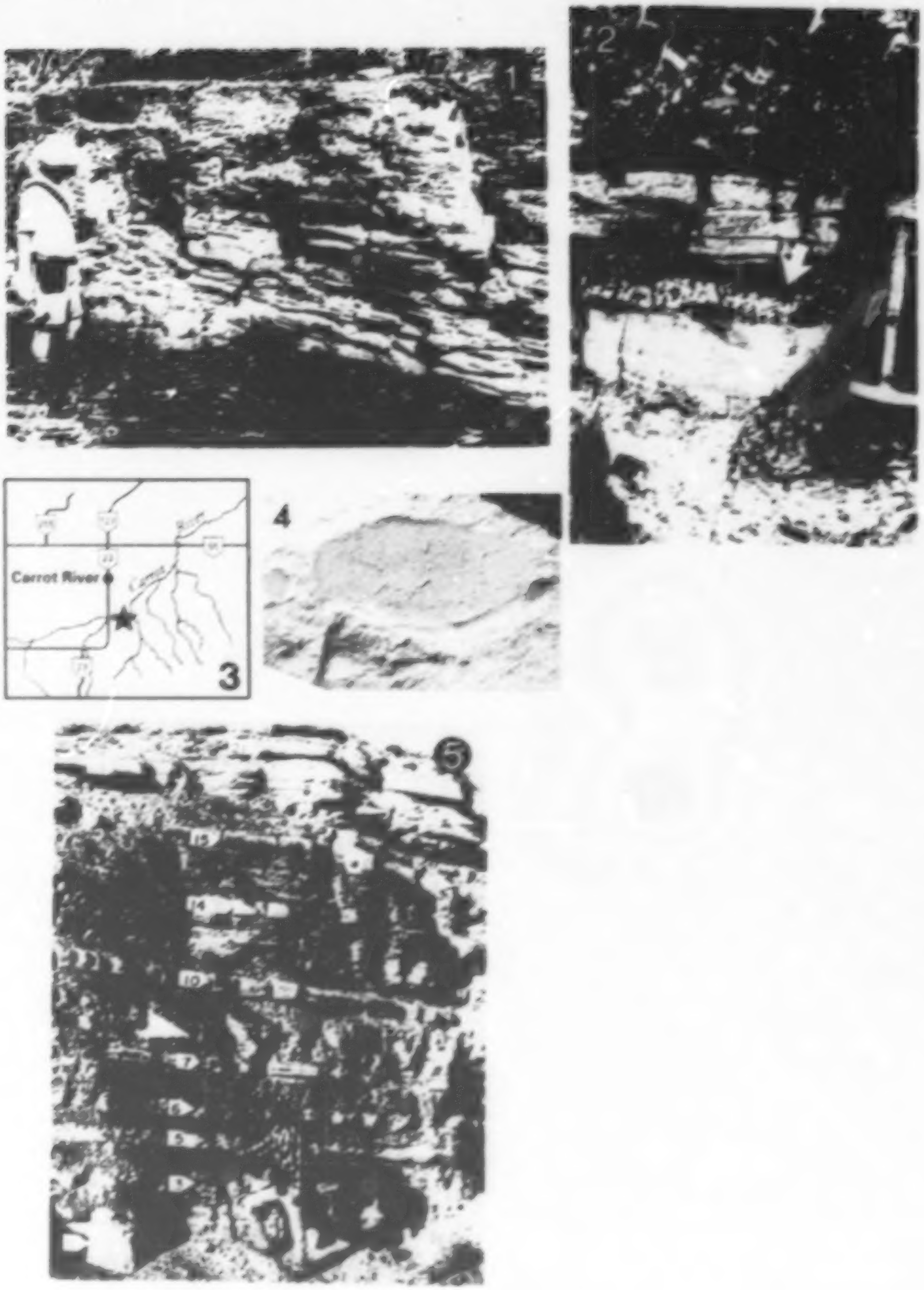

Figure 5 - (1) Cyclically interbedded laminated mudstone and marlstone facies of the Keld Member, Favel Formation: DH-2 locality, Carrot River; (2) Laurier Limestone Beds, uppermost Keld Member with marker Bentonite B-7 between indurated beds (at arrow): DH-2 locality, Carrot River; (3) map of Carrot River region: DH-2 and DH-3 sites (river-cut exposures; location shown by star) are separated by only 2.0 km; (4) Xiphactinus sp. - P2413.1a (x0.85), latex peel of large isolated scale: DH-2 locality, Carrot River; and (5) The Western Interior Reference Section (Pueblo, Colorado), shown are the basal ~11 regionally correlative limestone beds of the Bridge Creek Member, Greenhorn Formation (equivalent to upper Keld Member and lower Assiniboine Member in WCSB): Cenomanian-Turonian stage boundary indicated by white arrow (W. Elder for scale).

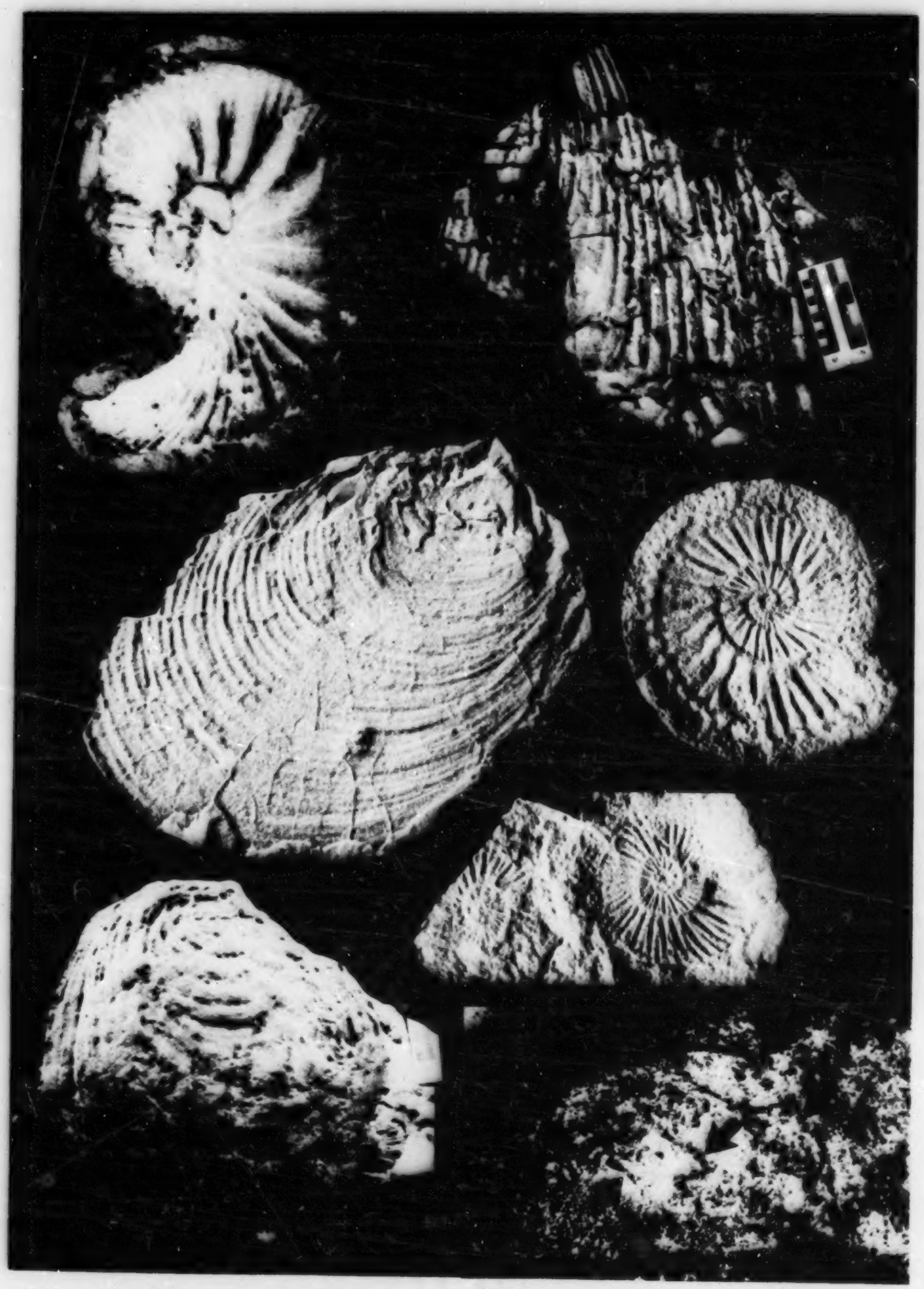

Figure 6 - (1) *Scaphites* aff. *ventricosus* Meek and Hayden (x0.84), macroconch?: Niobrara Formation float, Bainbridge River; (2) *Inoceramus* aff. *athabaskensis* McLearn, fragment of very large left valve (?), numerous epibionts are the encrusting oyster *Pseudoperna*: lower Favel Formation, Bainbridge River; (3) *Mytiloides hercynicus* (Petrascheck) - GSC 9297 (x0.84), lateral view of right valve, internal mold: Assiniboine Member, Carrot River (collected by F.H. McLearn, August 1935); (4) *Collignoniceras woollgari* (Mantell) - TMP 98.33.1 (x0.84), lateral view of adult macroconch (?), latex peel; (5) *C. woollgari* - TMP 98.33.2 (x0.84), lateral view of two adult specimens, latex peel: (4) and (5) are both from DH-2 locality (~1.0 m above Laurier Limestone Beds), Carrot River; (6) *Inoceramus* aff. *prefragilis* Stephenson (x0.0.17), lateral view of large right valve with protruding anterior margin: Bainbridge River?; and (7) *Thalassinoides*, ichnofossils (arrows) within marker bentonite B-7, between prominent limestones of the Laurier Limestone Beds, Favel Formation: Carrot River, camera lens cap for scale.

The Belle Fourche Member represents an overall third-order transgression (transgressive system tract), culminating with progradational facies being irregularly deposited during the latest Cenomanian throughout the WCSB. The Cruiser Formation and "Fish Scales Sandstone" are examples of these discontinuous sand bodies. The lower Keld *S. gracile* Zone is characterized by low-oxygen facies (black shale), and may represent either an unrecognized sequence boundary or a maximum flooding interval. The Laurier Limestone Beds were deposited during maximum flooding and relative sea-level rise. Subsequent regression and shoreline progradation resulted in deposition of the thin (<5 to 7 m) Jumpingpound Sandstone (*C. woollgari*: Figure 2) in Alberta. Although unmarked by a silty or sandy facies, the contact between the Keld and Assiniboine members occurs at this horizon in Saskatchewan.

The Marco Calcarenite may be genetically related to other late Middle Turonian "clastic wedges", such as the Ram Member of the Cardium Formation. Considering the observed degree of sediment bypass and starvation in the Pasquia Hills, it may be that the Marco Calcarenite records consecutive regressive (RST) and transgressive (TST) events. Its disarticulated and broken bivalve shell debris attests to high energy and, possibly, bottom-scouring waves inferring relatively shallow waters at time of deposition. The Morden Formation was probably deposited during the same interval when the two major progradations of the Ram and Cardinal members of the Cardium Formation occurred in the western shoreline facies belt. The dark organic-rich mudstones of the Morden Formation however, show no obvious evidence of clastic influx from the inferred Keewatin source area. Shared occurrences of molluscan index taxa have been the main guide for making onshore-offshore sequence stratigraphic correlations in the Western Interior. Much work remains in determining the precise stratigraphic positions of important erosional surfaces and the TST and RST between them.

a) Origin of Bentonites and Pasquia Bone Breccia

Two episodes of dramatic volcanism are known from the Albian-Cenomanian boundary interval in western Canada: emplacement of ultramafic diatremes of the Fort-à-la-Corne kimberlite swarm, associated with the Molanosa "highlands" of Saskatchewan (101 to 96 Ma BP, Kjarsgaard *et al.*, 1999), and eruption of the Crowsnest Volcanics (98 to 96 Ma BP) in southern Alberta. As such, the Westgate–Belle Fourche interval represents an active period of volcanism. At the Bainbridge River section, calcite crystal-lined "vugs" 4 to 8 cm in diameter were observed within concretionary bodies of the Pasquia Bone Breccia (Cumbaa and Tokaryk, 1999, Figure 4). Some of these cavities contained clumps of bentonitic material identical to the smectitic clays associated with the thicker marker bentonites, such as B7 in the Laurier Limestone Beds (Figure 6-7). These are interpreted to be remnants of volcanic ash erupted either to the north (Keewatin) or from the distant western cordillera. Elevated volcanic activity during the mid-Cretaceous has been attributed to higher oceanic spreading rates and a possible "superplume" event within the upper mantle (Larson, 1991).

Several hypotheses have been advanced to explain the distinctive bioclastic facies within the Pasquia Bone Breccia marker bed (Cumbaa and Tokaryk, 1999; Schröder-Adams *et al.*, 1999). Massive volcanic activity over the course of several months to years could have poisoned the Western Interior Seaway (via ash airfall on open water) to a level where most of its vertebrate inhabitants perished. Thick ash layers observed in cores of the Joli Fou and Viking formations from eastern Alberta (Cenomanian) may be additional evidence of such violent eruptions that changed adjacent epicontinental marine environments at a rate far exceeding that of the ability of teleost and elasmobranch populations to adapt.

In addition, if the X Bentonite, normally proximal to the *Ostrea beloiti* oyster biostrome, is present at the Bainbridge and Carrot River (DH-3) sections then it is the most widespread Cretaceous ash bed in North America. Moreover, if the X Bentonite represents a single eruptive event, then this episode of explosive volcanism is clearly greater than any recorded during human history. Basin-wide accumulations of the epifaunal oyster *O. beloiti* immediately above the X Bentonite may represent colonization by the so-called "disaster species" of Kauffman *et al.* (1991). They hypothesize that the oysters, gastropods, inoceramid bivalves, and other epifaunal organisms immediately above some Cretaceous ash layers imply that the ash itself provided a nutrient-rich substrate on which these animals could thrive, perhaps to a greater degree than under normal dysaerobic benthic conditions. Extensive networks of *Glossifungites* ichnofacies within bentonite B7 (Laurier Limestone Beds) indicate that burrowing organisms of that type were not significantly affected by large-scale volcanic events. In fact, the absence of *Thalassinoides* and *Psilonichnus* below and above this level at Carrot and Bainbridge rivers supports the possibility that volcanic ashes brought both death and opportunities for new life to the seafloor.

b) Gilbert Bedding Cycles

Decimetre-thick, cyclically bedded hemipelagic marlstone and organic-rich mudstone were initially recognized in Colorado and Kansas by Gilbert (1895, p121) as "regular alterations of strata" corresponding to "an astronomical cycle of known period". Gilbert used them to try to "deduce from this correlation an estimate in years of a portion of Cretaceous time." These time intervals are presently interpreted as Milankovitch cycles, representing the eccentricity (~100 to 126 Ka) and precession (~21 Ka) of Earth's orbital parameters (Fischer, 1980; Laferriere *et al.*, 1987). Nearly all formations within the Colorado Group exhibit such bedding (McNeil and Caldwell, 1981, Plate 5(D) and Plate 6(B); Schröder-Adams *et al.*, 1999, Figure 4A; and Figures 4-2 and 5-5 herein).

Individual limestone-shale couplets, reflecting the precessional cycle, have been correlated throughout Colorado and Kansas for the Cenomanian-Turonian Bridge Creek Limestone (Hattin, 1985; Elder *et al.*, 1994), and Turonian-Coniacian Fort Hays Limestone (Collom, 1991). Despite a relatively greater argillaceous component in the Colorado Group of Saskatchewan, such repetitive bedding can be observed in the field provided the rocks are not too weathered.

As outlined by Kauffman *et al.* (1991) and demonstrated by Elder *et al.* (1994), these Cretaceous mid-basinal couplets can be confidently correlated as 5th-order shoaling-upwards parasequences within the clastic-dominated shoreline facies belt of the Rocky Mountain Foothills. These are best observed in progradational regressive systems tracts (e.g. Dunvegan Formation), but are locally preserved in transgressive system tracts, such as the upper part of the Sunkay Member (Figure 4-2). Additional research may make it possible to correlate each of the bedding cycles ("parasequences") of the Keld and Assiniboine members to their counterparts in the Bridge Creek Limestone reference section in Colorado. Sufficient outcrop exists to undertake such ambitious correlations, but would require a closely spaced sampling program (5 to 10 cm intervals) and complete elemental and carbon/oxygen/TOC analyses.

4. Discussion and Conclusions

In the absence of stromatolites, rudistid bivalves, corals, or other phototrophic organisms, it is difficult to provide water depths of the Western Interior Seaway at given locations, particularly the Pasquia Hills. Cumbaa *et al.* (1992) and Cumbaa (1999) have argued that, in this area, bone beds, certain terrestrial palynomorph assemblages, storm-tolerant oyster species, and tidal-like bedding are suggestive of a nearshore position for parts of the Ashville Formation. Re-examination of facies and ostreiid communities, however, provide less conclusive results. The Colorado Group above the Westgate Member of the Ashville Formation in Saskatchewan appears to have been deposited at least 100 km from shore. Taking into consideration the typical benthic association (inoceramid bivalves and rare oysters) of these fine-grained, laminated non-rippled sediments, the presence of *Glossifungites* and *Zoophycos*-type ichnofacies, the dominance of planktonic foraminifera, and the nature of shark and ray faunas, it is estimated that the depth of the seaway was 60 m to 80 m maximum and 30 m to 40 m minimum.

In summary, outcrops in the Manitoba Escarpment of east-central Saskatchewan of the Keld and Assiniboine members (Favel Formation) have produced the oldest Cretaceous birds, turtles, large bony fish (*Xiphactinus*), and marine crocodylomorph (*Terminonaris*) known from North America. The undisturbed skeletons and molluscs suggest stable, quiet water depositional environments. Regional correlation using diagnostic marker beds, 12 bentonites (volcanic ash beds), and molluscan biozone index taxa (inoceramid bivalves and ammonites) allows comparison with coeval fine-grained marine deposits of the Blackstone Formation, Alberta Foothills, and with the Pueblo Western Interior reference section.

The thin, discontinuous, silty, fine-grained sandstone beds within the upper Ashville Formation (early Cenomanian) are believed to have been derived from an unknown upland to the north (presently exposed Precambrian Shield). It is considered unlikely that these clastics were derived and transported ~1000 km from the actively overthrusting western hinterland. Fewer than 5.0 m above this interval, near the Ashville-Favel contact, a prominent concretionary "bone conglomerate" layer of shark and fish bones, scales, and teeth is correlated with the Fish Scales Formation of the more proximal portion of the Western Canada Sedimentary Basin in Alberta. The origin of this highly condensed interval may represent a combination of mass mortality resulting from submarine/nearshore volcanism, and/or eustatic changes.

Biostratigraphic control of Colorado Group strata in the Pasquia Hills by means of molluscan macroinvertebrates is based on the distribution of numerous inoceramid bivalves and planispiral and scaphitid ammonites. The Ashville-Morden interval spans the Cenomanian and Turonian stages of the mid-Cretaceous, a period of ~9.0 Ma (97.0 to 88.0 Ma BP). Relative rates of sediment accumulation between the Alberta foredeep (Rocky Mountain Foothills region) and Saskatchewan were approximately 48:1. Thus the Colorado Group along the Manitoba Escarpment is constituted of highly condensed marine hemipelagic and pelagic facies.

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Cretaceous Stratigraphy in Four Cores from the Vicinity of the Fort-à-la-Corne Kimberlite Field, East-central Saskatchewan – Preliminary Results

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McNeil, D.H. and Gilboy, C.F. (2000): Cretaceous stratigraphy in four cores from the vicinity of the Fort-à-la-Corne kimberlite field, east-central Saskatchewan – preliminary results; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

1. Introduction

In this paper, we examine the stratigraphic relationships of two intriguing and significant features of the Cretaceous geological record in east-central Saskatchewan. The first is the occurrence of diamond-bearing kimberlite bodies in Late Albian strata (Figure 1). The second is the occurrence of unconformities and condensed stratigraphic units that are of Early Cenomanian to Early Campanian age and that converge towards the kimberlite field but were developed after kimberlite activity ceased (Figure 2).

At least 69 kimberlite bodies have been documented in east-central Saskatchewan (Jellicoe *et al.*, 1998). Kimberlite activity must have been triggered through deep-seated tectonic controls, although the exact mechanism has not been documented. Jellicoe *et al.* (1998) suggested that the Saskatchewan Craton (Chiarenzelli *et al.*, 1996) provided a thick lithospheric keel which is thought to be important in the generation of kimberlitic magmatism. A significant characteristic of the kimberlite deposits is that no pipes of diatreme facies have yet been drilled. The known kimberlites consist only of volcaniclastic "crater facies" deposits and associated marine and fluvial reworked sedimentary kimberlite facies. They are contained within terrestrial to marine sedimentary rocks mainly of Albian age (one Cenomanian age has been recorded). The marine reworked kimberlitic material may hold the greatest promise for concentrations of diamonds.

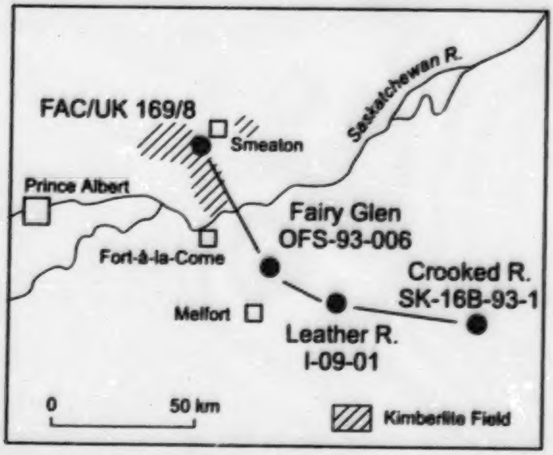

Figure 1 - Location of four cores studied in the Fort-à-la-Corne area of east-central Saskatchewan.

The underlying cause of the unconformities and condensed sections in Cretaceous strata is not well established. In different combinations, tectonic movement, eustasy, movement of water masses, and sedimentation rates could have been responsible. Numerous previous studies (e.g. North and Caldwell, 1975; Williams and Baadsgaard, 1975; McNeil and Caldwell, 1981; McNeil, 1984) have documented major unconformities above and below the First and Second White Specks formations and the Pembina Member, Pierre Shale. A clear understanding of the causal mechanisms and the detailed stratigraphy has not, however, been reached. Little or no Cretaceous stratigraphic information existed for the Fort-à-la-Corne area prior to recent research stemming from kimberlite exploration. Current research will shed light on the Cretaceous stratigraphic anomalies of the area in addition to kimberlite-related stratigraphy.

2. Previous Work and Methodology

In order to establish the stratigraphic relationships between Cretaceous sediments and kimberlites in the Fort-à-la-Corne area, preliminary lithostratigraphic and biostratigraphic data are presented from four cores which form a 126 km long cross-section through east-central Saskatchewan (Figure 1). The cross-section illustrates the position of kimberlites in the Smeaton FAC/UK 196/8 core relative to non-kimberlitic Cretaceous strata cored in three wells: the Rhonda Fairy Glen OFS 93-006 (13-35-47-18W2), the Kennecott Leather River I-09-01 (1-4-45-10W2), and the Kennecott Crooked River SK-16B-93-1 (4-23-46-16W2). Previous studies on the Smeaton core (Leckie *et al.*, 1997) documented the occurrence and characteristics of the kimberlites which consist of pyroclastic airfall crater deposits overlain by marine sedimentary reworked kimberlite facies and marine mudstones of the Late Albian Westgate Formation.

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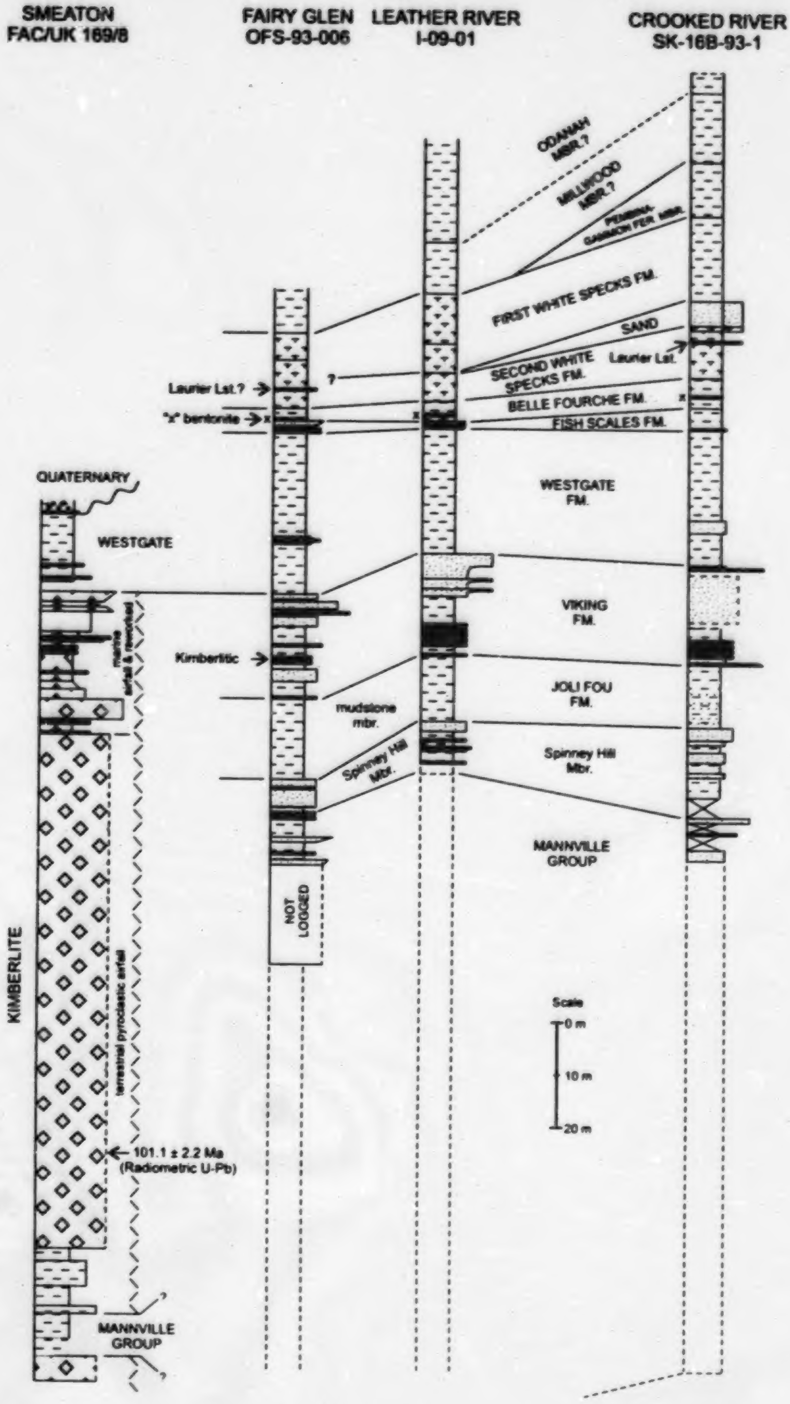

Figure 2 - Stratigraphic cross-section of cores from four boreholes in the Fort-à-la-Corne area, east-central Saskatchewan. Datum is the base of the Fish Scales Formation. The Cretaceous stratigraphy and kimberlitic succession in the Smeaton FAC/UK 169/8 borehole is summarized from Leckie** et al. **(1997). The thickness of the Mannville Group is projected from nearby exploration wells. The Smeaton FAC/UK 169/8 core is stored at the Geological Survey of Canada (Calgary) and the other three cores are stored at the Saskatchewan Energy and Mines Subsurface Geological Laboratory in Regina.

McNeil and Gilboy (1999) presented a preliminary correlation between the Leather and Crooked River cores. White *et al.* (1999) reported on the Albian-Cenomanian chemostratigraphy and sequence stratigraphy in the Crooked River core. In the current study, the Fairy Glen (FG), Leather River (LR), and Crooked River (CR) cores have been described lithologically and sampled for geochemical, nannofossil, palynological, and microfossil analysis. Stratigraphic descriptions have been completed for all the wells and preliminary paleontological data on the foraminifera are now available for the LR and CR cores.

3. Kimberlites

The Fort-à-la-Corne kimberlite field contains at least 69 kimberlite occurrences (Jellicoe *et al.*, 1998), all of which consist of volcaniclastic "crater facies" deposits. Volcaniclastic kimberlite deposits of this type are relatively uncommon as most kimberlites occur as diatreme pipes in eroded Precambrian terrains. Recent radiometric age determinations by Larry Heaman (University of Alberta) and Bruce Kjarsgaard (Geological Survey of Canada, Ottawa) indicate that ten of twelve kimberlite bodies examined in the Fort-à-la-Corne field were emplaced between 99 and 101 Ma (Kjarsgaard, pers. comm., 2000). Many kimberlite bodies in Fort-à-la-Corne field have been cored; but, the Smeaton one is the only one which has been geologically described in detail (Leckie *et al.*, 1997). Therefore it is utilized in the stratigraphic cross-section linking the kimberlites to Cretaceous strata to the southeast (Figure 2).

The main kimberlite section in the Smeaton core is a 77 m-thick conformable succession of pyroclastic lapilli- and olivine-dominated airfall deposits overlain by 25 m of subaqueous pyroclastics and marine reworked kimberlite facies (Leckie *et al.*, 1997). An older, undated, fluvial-reworked kimberlite also lies at the base of the Smeaton core below Middle Albian Cantuar sediments. A U-Pb radiometric age of 101.1 ±2.2 Ma was determined from perovskite in the lower part of the terrestrial kimberlite section. Marine mudstone sediments of the lower Westgate Formation were estimated to be ca. 100 Ma based on regional biostratigraphic correlations with the standard zonations and chronologies for the Western Interior Cretaceous (McNeil *et al.*, in press). Biostratigraphic data from agglutinated foraminifera indicate that the lower part of the Westgate Formation is fully preserved in a transgressive facies overlain by a truncated regressive marine facies. Stratigraphic relationships and radiometric ages, therefore, confirm that the main kimberlite section in the Smeaton core was emplaced at the time Viking Formation sediments were being deposited in the Western Canada Sedimentary Basin (WCSB). This appears to be corroborated in the Fairy Glen core, 44 km to the southeast (Figure 2), by possible indicator minerals (garnets?) and thin kimberlitic rocks in the lower part of the Viking Formation. The absence of the uppermost Mannville Group, the entire Joli Fou Formation, and typical Viking Formation sediments at the Smeaton location remains enigmatic. Available data suggest that the kimberlite explosive eruption must have displaced the missing units, but it is not clear how this would occur and leave the Cantuar section intact, unless the explosive forces were laterally abrupt and violent near the surface. Alternatively, kimberlite deposition might have occurred at the same time as upper Mannville sedimentation.

In the Smeaton core, microdiamonds 5 to 25 µm in size were recovered from the kimberlite airfall facies (Leckie *et al.*, 1997). In the marine-reworked facies, indicator minerals were abundant in samples that were processed for microfossils from 115.5 to 121.1 m. At 115.1 to 115.22 m, a coarse, diamond-bearing transgressive lag deposit is present. Unfortunately, a 2.3 m gap in the core occurs immediately above the transgressive lag. McNeil and Gilboy (1999) have illustrated stratigraphic relationships between the kimberlite and the Westgate and Viking formations in the Smeaton and Crooked River cores.

4. Cretaceous Strata, Unconformities, and Condensed Sections

Cretaceous strata in the Fairy Glen, Leather River, and Crooked River cores can be grouped into three discrete packages that appear to have undergone markedly different conditions of sedimentation. The packages consist of the Mannville Group to Westgate Formation (more or less continuous non-marine to marine sedimentation), the Fish Scales Formation to the Pembina Member of the Pierre Shale (marine strata most affected by unconformities and condensation), and the Millwood and Odanah members of the Pierre Shale (continuous uniform marine sedimentation). It is not known if the Cretaceous stratigraphic relationships were influenced by mechanisms responsible for kimberlitic activity. The Albian sedimentary package does not seem to have been affected in any of the cores. In contrast, the Cenomanian–earliest Campanian package is increasingly condensed and affected by unconformities towards the kimberlite fields.

a) Mannville Group to Westgate Formation

Stratigraphic continuity appears to have been the norm during upper Mannville Group sedimentation through that of the Westgate Formation. The emplacement of kimberlites in the Fort-à-la-Corne area apparently had little affect on Albian depositional patterns to the southeast as there is no obvious stratigraphic influence or sign of kimberlitic eruptions except for two thin layers of possible kimberlitic material in the Viking Formation, Fairy Glen core (Figure 2). At the site of the kimberlite craters, however, it is a different story. In the Smeaton core, uppermost Mannville to Viking sediments are absent. This section is made up of kimberlitic rocks ca. 101 Ma. Marine reworking of the uppermost kimberlite represents the marine transgressive systems tract that constitutes the upper part of the Viking Formation.

The upper part of the Mannville Group has been cored in the three boreholes studied, but stratigraphic subdivisions within the group have not been picked. Its overall thickness is approximately 90 to 150 m based on interpretations from nearby exploration wells. Relief on the sub-Cretaceous unconformity apparently controls marked variations in the thickness of the Mannville Group. Sediments that are present in the core consist of terrestrial shales, siltstones, and sandstones. Some units are highly bioturbated, plant remains are common, and highly organic layers including coaly beds up to 15 cm thick are abundant. The upper contact with the Spinney Hill Member of the Joli Fou Formation is sharp and occurs above calcite- and pyrite-cemented sandstones that are highly bioturbated. A transgressive marine surface of erosion probably marks the boundary with the overlying Joli Fou Formation.

The Joli Fou Formation maintains a uniform thickness of 26 or 27 m in the FG, LR, and CR cores. Its lower part consists of the Spinney Hill Member and the upper part is informally referred to as the Joli Fou mudstone member. The Spinney Hill thins slightly towards the northwest from 15.3 to 13.6 m and the overlying mudstone member thickens proportionately. The Spinney Hill is characterized by very fine- to fine-grained glauconitic sandstone beds, 10 cm to 2.5 m thick, with thin mudstone and shale interbeds. Bedding is generally low angle with hummocky cross-stratification also present. Sandstones are moderately to highly bioturbated with *Terebellina*, *Planolites*, *Chondrites*, *Zoophycos*, and *Asterosoma* present. Fine-grained sedimentary rocks contain *Chondrites* and *Planolites*.

The Spinney Hill Member contains a prolific assemblage of agglutinated foraminifera of the *Haplophragmoides gigas* Zone of early Late Albian age. A concentration of fish fragments at the base of the member (CR core, 237 m) probably represents a transgressive lag and the initial flooding surface for the Joli Fou sea. Foraminifera consist of robust, coarsely arenaceous species dominated by *Lagenammina*, *Ammodiscus*, *Haplophragmoides*, *Ammobaculites*, *Ammobaculoides*, and *Caronia* [*Gaudryina*] suggesting high-energy, shallow-shelf environments of deposition.

The mudstone member of the Joli Fou Formation consists of grey shales or mudstones that are generally non-bioturbated but contain some beds with *Chondrites* and *Planolites*. Very fine-grained sandy interbeds a few centimetres in thickness are common. In both the LR (188 to 190 m) and CR (221 to 225 m) cores, the lower part of the mudstone member is essentially barren of benthic foraminifera, is non-bioturbated, but contains fish debris. This section is presumed to be an anaerobic biofacies. Its stratigraphic position suggests that it is a regional expression of the Late Albian oceanic anoxic event 1C (Jenkyns, 1980). Above the anaerobic biofacies, to the upper contact with the Viking Formation, a new foraminiferal assemblage occurs, dominated by *Saccammina*, *Miliammina*, *Haplophragmoides*, and *Gravellina*. This assemblage suggests a regressive, shallow marine, low salinity environment of deposition. *Haplophragmoides gigas* is absent in this assemblage except for an anomalous, but abundant, occurrence at 217 m in the CR core. At least on a local basis, foraminiferal distributions indicate that standard zones of *H. gigas* and *M. manitobensis* (Caldwell *et al.*, 1978) require refinement to take into account increased biostratigraphic resolution.

The Viking Formation has a uniform thickness of 18 or 19 m in the FG, LR, and CR cores. The lowermost Viking beds in the LR and CR cores consist of alternating very fine-grained muddy sandstone and laminated silty shales (60:40 ratio), mostly intensely bioturbated (*Chondrites*, *Terebellina*, and *Teichichnus*). In FG, thicker sands (up to 2 m) and shale or mudstone intervals characterize the lowermost Viking beds. In the middle part of the Viking in the FG core, a shaly interval contains two fine-grained dense layers of possible kimberlitic material 10 and 15 cm thick. The beds also contain quartz grains, fish debris, and possible diamond indicators (garnets?). If correctly identified, this is the only occurrence of kimberlite and indicator minerals yet found in the cores to the southeast of the Fort-à-la-Corne area. They probably represent a marine-reworked airfall deposit or the distal extension of marine-reworked kimberlite from the Fort-à-la-Corne area, only 20 km to the northeast. In the LR and CR cores, these middle mudstone beds of the Viking contain a foraminiferal assemblage dominated by *Saccammina*, *Miliammina*, and *Verneuilinoides* typical of a marginal marine, perhaps lagoonal, environment. The upper part of the Viking is sand rich in all three cores, but significant differences exist in the internal stratigraphy between the cores. For example, sandstone in the upper part of the Viking in CR contains terrestrial microfossils (megaspores, coal, amber), whereas the upper sandstones in the LR core contain marine microfossils representing the early transgressive part of the overlying marine cycle. Work on the sequence stratigraphic relationships in these rocks is currently in progress, but a preliminary sketch of the sequence boundary within the Viking Formation relative to the Smeaton kimberlite section is shown in Figure 3.

The Westgate Formation is predominantly made up of shale and mudstone 22 to 30 m thick. A 1 or 2 m thick bioturbated sandy unit typically occurs in the lower half of the formation. Most of the mudstones and fine sandstones or siltstones of the Westgate are slightly to moderately bioturbated (*Chondrites*, *Terebellina*, and *Teichichnus*, with possible *Planolites* and *Helminthopsis*). The lower contact with the Viking Formation occurs at a transgressive lag (flooding surface) that can be recognized in all four cores. Benthic foraminifera of the Late Albian *Miliammina manitobensis* Zone are abundant above the flooding surface and provide a record of transgression and regression through the Westgate (McNeil and Gilboy, 1999; McNeil *et al.*, in press). An anomalous occurrence of the *Verneuilinoides perplexus* Zone in rubble at 181 m in the CR well led to the erroneous placement of the upper boundary with the Fish Scales Formation (sequence boundary) at 181.9 m. The

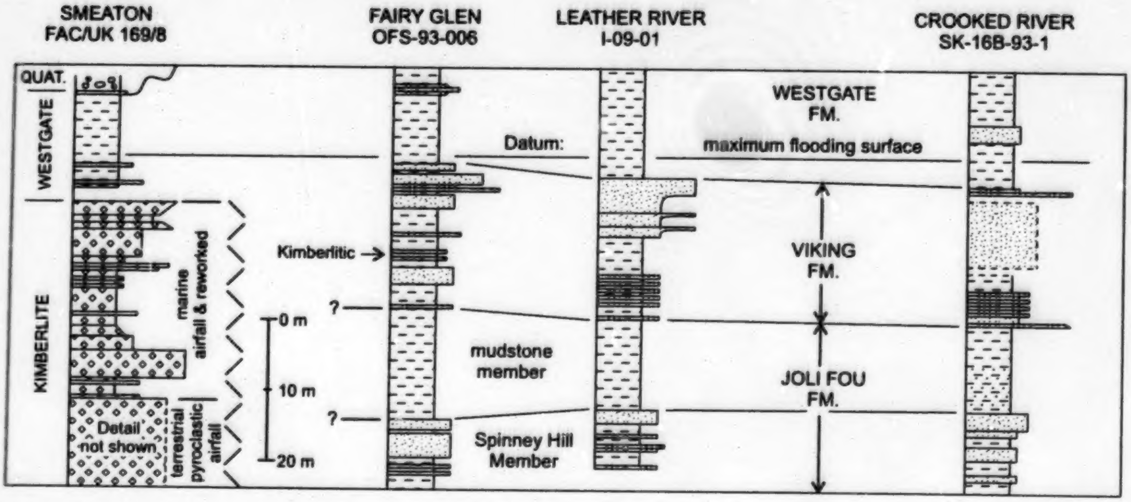

Figure 3 - Stratigraphic position of kimberlite rocks in the Smeaton FAC/UK 169/8 core relative to Cretaceous stratigraphic units in the Fairy Glen, Leather River, and Crooked River cores. The maximum flooding surface within the lower Westgate Formation is drawn on the basis of microfossil data. A radiometric age of 101.1 ±2.2 Ma in the lower part of the kimberlite succession suggests that the kimberlites are of Viking age.

correct contact between the Westgate and Fish Scales occurs at 172.5 m in the CR core as originally designated by Gilboy (1997). Resolution of the foraminiferal distributions and zonation through this section is currently in progress. Age assignments might also be revised considering: 1) McNeil and Caldwell's (1981, Figure 9) correlation of the upper Westgate with the Mowry Shale, and 2) revision of the Albian-Cenomanian to the base of either the *Neogastroplites cornutus* or *N. haasi* Zone (Cobban and Kennedy, 1989; Obradovich, 1993). This would place the Albian-Cenomanian boundary at about the middle of the Westgate Formation, rather than at its historical position at the base of the Fish Scales marker in the Western Canada Sedimentary Basin.

b) Fish Scales Formation to Pembina Member, Pierre Shale

Strata of the Fish Scales Formation through to the Pembina Member of the Pierre Shale form a stratigraphic wedge that thins northwestward due to the combined effects of unconformities and stratigraphic condensation towards the Fort-à-la-Corne kimberlite field. This unconformity-riddled wedge thins from about 52 m in the Crooked River core to about 18 m in the Fairy Glen core. Lithostratigraphic and biostratigraphic work, essential to the interpretation of these units, is still in progress, so their stratigraphic relationships are only briefly touched on here. The wedge is part of a regional thinning (Figure 4) of the Upper Colorado Subgroup towards central Saskatchewan (Williams and Burk, 1964, Figure 12-9). It is also consistent with a dome-shaped structural high in the Fort-à-la-Corne area (Simpson, 1982, Figure 37), and a weak structural high on a regional cross-section through central Saskatchewan (Hutt, 1963). Similar stratigraphic relationships have been documented from the Saskatoon area by North and Caldwell (1975). Using foraminiferal biostratigraphy, they documented unconformities beneath both the First and Second White Specks formations in the potash cores to the east and west of the Saskatoon area. This indicates that a

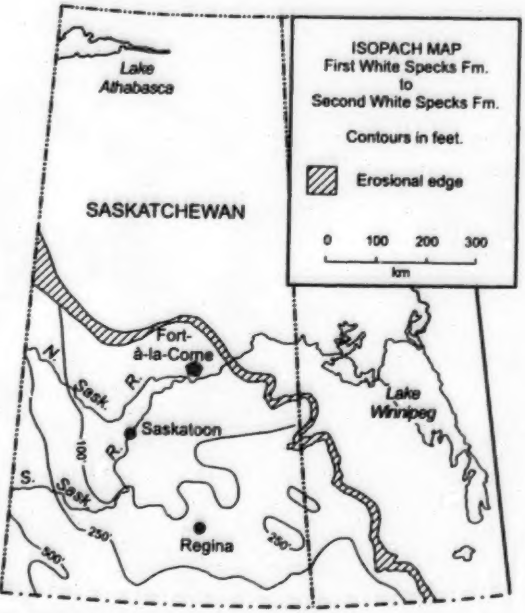

Figure 4 - Isopach map of the First to Second White Specks formation in Saskatchewan and southwestern Manitoba (redrawn from Williams and Burk, 1964). Note contour intervals are in feet.

regional southwest-northeast structural high may have extended from the Saskatoon area to the Fort-à-la-Corne area.

The Fish Scales Formation consists of shales, siltstone, and very fine-grained sandstones, locally calcite-cemented, with a sand/shale ratio of approximately 50:50. Fish debris is typically concentrated along bedding planes. In the LR core, the Fish Scales Formation consists of three coarsening-upward cycles. The formation thins steadily northwestward from 3.7 m in CR to 1.25 m in FG where thin siltstones and sandstones make up the entire unit. The lower contact is sharp with pyrite-filled burrows in the LR core and is a regional sequence boundary in the Western Interior. Its upper contact is unconformable with the overlying Belle Fourche Formation.

Stratigraphic and sedimentological interpretations of the Fish Scales beds are only gradually unfolding despite their having been recognized as a regional marker for decades (Gleddie, 1954). McNeil (1984) considered them to represent a basin-wide shoaling event with clastics transported into the basin from west and east. The Fish Scales sandstones in Manitoba and eastern Saskatchewan correlate with the D sandstone tongue of the Dakota Group extending into the Graneros Shale in the Denver Basin (McNeil, 1984). Leckie *et al.* (1992) recognized three units in the Peace River area: a lower bioturbated unit with terrestrial organic matter, a middle unit formed during rising sea level with anoxic substrates rich in fish debris, and an upper organic-rich unit with progressively more clastic sediment upsection. This description matches generally with the stratigraphic section in the FG, LR, and CR cores which consists of the distal, basinal representation of the Fish Scales beds condensed over a regional high in central Saskatchewan. The anoxic unit probably represents an Early Cenomanian regional oxygen-depletion event similar to that described by Kauffman and Hart (1996).

The Belle Fourche Formation is apparently unconformity bounded and thins from 5.7 m in Crooked River to 2.2 m in Fairy Glen. The "X" bentonite, 50 cm thick in the CR core, occurs at about the middle of the formation along with the thin, calcarenitic *Ostrea beloiti* beds. The *Verneuilinoides perplexus* Zone occupies the lower part of the Belle Fourche in the CR core. In LR and FG cores, however, an unconformity cuts out the lower half of the Belle Fourche and, as a result, the "X" bentonite lies directly on the Fish Scales Formation and *V. perplexus* Zone is absent.

The Second White Specks Formation (Favel Formation) unconformably overlies the Belle Fourche in all three cores (FG, LR, CR) and contains the planktonic foraminiferal zone of *Hebergella loetterlei*. In the LR core and probably the FG core, however, the lower part of the *H. loetterlei* Zone (i.e. the *Clavihedbergella simplex* Subzone) is absent by unconformity. Thin limestones (5 to10 cm) in the formation are probably the Laurier Limestone beds, which correlate with the Bridge Creek Limestone in the U.S. Western Interior and represent maximum flooding of the Early Turonian Greenhorn sea, hence their widespread distribution and preservation. The upper contact is unconformable with the First White Specks Formation in LR and CR, and data from the FG are presently not available.

The Morden Shale, although recorded in the CR core by Gilboy (1997) and McNeil and Gilboy (1999), has not been verified in the LR and CR cores by paleontological analysis. Foraminiferal data indicate that the First White Specks Formation in LR, for example, lies directly on the Second White Specks (Figure 2). In Crooked River, however, a sandstone unit is present between the First and Second White Specks formations. This unit occupies the same stratigraphic position as numerous Western Interior sandy units including the Late Turonian–Early Coniacian Cardium Formation in Alberta, the Late Turonian Turner Sandstone Member of the Carlile Formation in the Black Hills area, and the late Middle Turonian Codell Sandstone Member, Carlile Shale, in Kansas. The sandstone contains agglutinated foraminifera, numerous bentonites, burrows of *Condrites* and *Terebellina*, and traces of fusain. Further work on its age, sedimentology, and origin are in progress, but it no doubt represents a major regressive event and contains a major sequence boundary in the WCSB.

The First White Specks Formation (Niobrara Formation) thins from 21 m in CR to 15.3 m in LR (Figure 2), but its lower contact in FG has yet to be identified using paleontological data. Its lithology consists of white speckled shale, in places highly calcareous, with fish remains, thin bentonites, and mollusc shell fragments. A variety of "Niobrara" foraminifera are present, including planktonics and both agglutinated and calcareous benthics, but foraminiferal distributions are discontinuous in the LR and CR cores and many samples were barren. The variations in fossil content suggest a complicated depositional history, perhaps affected by regional or oceanic anoxic events, facies changes, or erosional episodes, which have yet to be resolved for this area of the Western Interior Basin. A major regional unconformity affects the uppermost White Specks Formation, as documented by Williams and Baadsgaard (1975) in southeastern Saskatchewan and McNeil (1984) in the Manitoba Escarpment.

The Gammon Ferruginous and Pembina members of the Pierre Shale occur only in the Crooked River core and are difficult to separate due to lithological similarities and poor fossil recovery. The Pembina Member is documented in the CR core (122 to123 m) by the occurrence of *Bathysiphon vitta* with a distinctive black organic coating common on the exterior of its test. Typical of the Pembina, numerous bentonites occur in the CR core. In the FG and LR wells, both the Gammon Ferruginous and Pembina members are cut out by an unconformity. A similar unconformity occurs at this stratigraphic level in the Manitoba Escarpment as illustrated by McNeil and Caldwell (1981) and McNeil (1984).

c) Millwood/Odanah Members, Pierre Shale

The uppermost Cretaceous strata in the FG, LR, and CR cores are assigned to the undivided Millwood/ Odanah members of the Pierre Shale. This undivided unit is 80 m thick in the Crooked River core, but the upper contact was not cored. Its lithology is remarkably uniform consisting of pale grey mudstone to darker grey shale. Sideritic concretionary layers of 4 to 10 cm in thickness are common, as are *Chondrites* burrows, fish remains, and mollusc shells. The Millwood-Odanah contact might occur at 107.5 m in the CR core where there is a change in the benthic foraminiferal assemblage. Core from 107.5 to 116 m contains a variety of agglutinated foraminifera including *Spiroplectammina* sp., as well as the calcareous benthic *Gavelinella pertusa* which occurs in the Millwood Member in the Manitoba Escarpment (McNeil and Caldwell, 1981). In CR core, above 107 m, the foraminiferal assemblage is relatively uniform consisting of *Bathysiphon*, *Ammodiscus*, *Glomospira*, *Haplophragmoides*, and *Dorothia*, an assemblage which suggests relatively deep water. Interpretations on the Millwood/Odanah are sketchy at present, as further research on its biostratigraphy and geochemistry is in progress.

5. Summary of Current and Ongoing Work

The lithostratigraphic and biostratigraphic work that has been presented briefly in this report, combined with previous geological studies in the Fort-à-la-Corne area (e.g. Leckie *et al.*, 1997), is sufficient to establish the stratigraphic position of kimberlitic anomalies relative to Cretaceous rocks of the Fort-à-la-Corne area. The events that led to the Late Albian kimberlite explosion (Smeaton location) apparently had little affect on the Cretaceous sedimentary strata to the southeast of the Fort-à-la-Corne area, as units show no particular modification in thickness or character in the direction of the kimberlites. Possible evidence of kimberlitic activity occurs 20 km from the southeast margin of the Fort-à-la-Corne kimberlite field within the Viking Formation in the Fairy Glen core as indicated by indicator minerals (garnets?) and thin dense rocks of apparent kimberlitic origin. This stratigraphic position is consistent with a previously reported age of 101.1 ±2.2 Ma from the Smeaton kimberlite (Leckie *et al.*, 1997), and the general recognition that the majority of the volcanism at Fort-à-la-Corne occurred in the time interval from 99 to 101 Ma (Kjarsgaard, pers. comm., 2000). Although the kimberlitic beds in the Viking are very thin, it is possible that thicker and more numerous beds could occur closer to the kimberlite occurrences. Concentrations of indicator minerals and diamond occurrences in marine reworked kimberlite at the Smeaton locality (Leckie *et al.*, 1997) make this facies a potential target for further diamond exploration.

The convergence of unconformities and condensed sections in Cenomanian to earliest Campanian strata towards the Fort-à-la-Corne kimberlite fields might be related to regional tectonic uplift in central Saskatchewan, rather than kimberlitic events *per se*. The pattern of condensation follows regional trends recognizable over a broad area of central Saskatchewan trending from the Fort-à-la-Corne area southwest through the Saskatoon area. Many of the unconformities are recognized also in the Manitoba Escarpment and elsewhere in the Western Interior Cretaceous Basin, emphasizing a regional, rather than local, control. However, this does not rule out the possibility of uplift in the Fort-à-la-Corne area during or prior to kimberlitic activity.

Further work on the biostratigraphy and geochemistry of these cores will document the unconformities and the internal stratigraphy and contents of the condensed strata. A thorough sequence stratigraphic analysis of the entire section will establish these cores as important reference sections at the geographic centre of North American, near the northeastern erosional edge of the Cretaceous System.

6. Acknowledgments

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Lithofacies Architecture of the Milk River Formation (Alderson Member of the Lea Park Formation), Southwestern Saskatchewan and Southeastern Alberta – Its Relation to Gas Accumulation

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Ridgley, J.L. (2000): Lithofacies architecture of the Milk River Formation (Alderson Member of the Lea Park Formation), southwestern Saskatchewan and southeastern Alberta – its relation to gas accumulation; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1.

1. Introduction

Large accumulations of biogenic gas are known to occur in shallow (<1000 m) Cretaceous reservoirs of the Northern Great Plains (mainly Montana) and southeastern Alberta and southwestern Saskatchewan, Canada. The 1995 U.S. Geological Survey national oil and gas assessment made a mean estimate of 1.15 to 1.18×10^{12} m^3 (41 to 42 trillion cubic feet) of potential additions to reserves of continuous-type (unconventional) gas in Cretaceous shallow biogenic gas plays of northern and central Montana (Rice and Spencer, 1995). About 90 percent of the 1995 gas estimate was in hypothetical plays, and of this percentage, over one-half was based primarily on similarity of the potentially productive facies in Montana to the facies that host large shallow biogenic gas resources in southeastern Alberta and southwestern Saskatchewan. The controls on the hypothetical play boundaries were poorly understood in 1995. Sedimentologic, structural, and hydrologic studies of the important shallow gas-producing formations in southwestern Saskatchewan and southeastern Alberta have been undertaken in order to better understand the relative importance of each of these parameters as a control on the site of the shallow gas accumulation. The objective of this research is to apply the Canadian model to Montana where gas might be expected to occur.

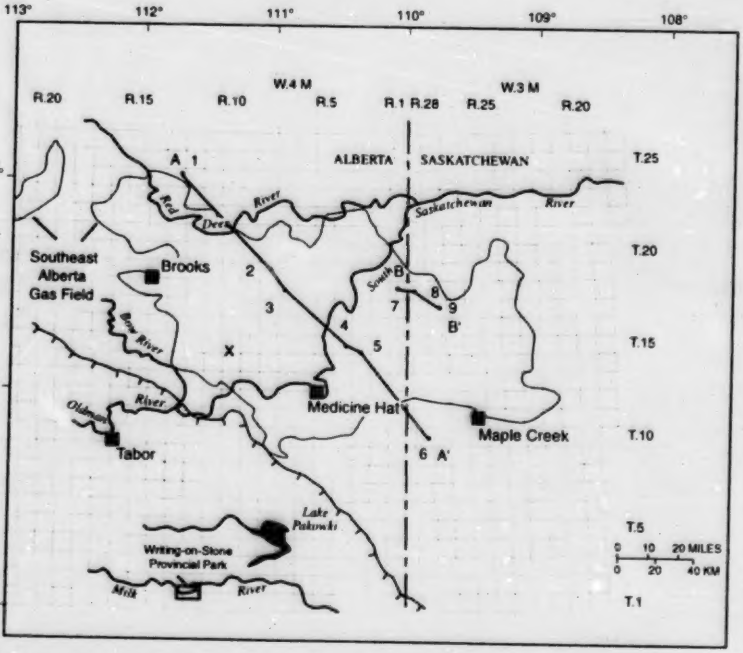

Figure 1 - Map showing location of core holes and cross-section A-A' and B-B', depositional extent of Virgelle Sandstone (hachured line), Writing-on-Stone Provincial Park, and location of southeast Alberta gas field (Alberta and Saskatchewan). Type Alderson section ARCO Alderson well 10-14-15-10W4 is shown as X.

The Milk River Formation is one of the principal formations that yields shallow gas in the large southeast Alberta gas field (Alberta and Saskatchewan) (Figure 1). Gas in the Milk River occurs in interbedded, very fine-grained sandstone and shale reservoirs. In contrast, shallow gas production in the correlative Eagle Sandstone in Montana is from fine- to medium-grained sandstone reservoirs. Gas in both the Milk River and Eagle Sandstone is of biogenic origin. Whereas gas in the Eagle Sandstone reservoirs has been assessed as a conventional gas accumulation, gas in the Milk River Formation would be considered a type of unconventional gas accumulation that fits the "continuous-type" gas accumulation category first defined and used in the 1995 U.S.G.S. national assessment (Schmoker, 1995). Continuous-type accumulations are considered to be large, low-grade, non-conventionally reservoired (i.e. not bounded by a downdip water contact) gas concentrations that crosscut lithologic boundaries on a regional scale. Where they occur, continuous-type gas accumulations are thought to be mostly gas-charged everywhere in the gas-bearing interval, although the gas may not always be economic. Other characteristics of continuous-type gas accumulations include an updip water contact, the insignificance of conventional traps and seals, a close association of reservoir with source rock, and low reservoir permeability in facies that have large areal extent. Application of the concepts of continuous-type gas accumulations to the area of the Northern Great Plains (Montana) and southeastern Alberta and southwestern Saskatchewan indicates that gas resources should be present over an area greater than that in which this commodity is currently being exploited. This report presents preliminary correlations of lithofacies along two strike-oriented transects (Figure 1) within the Milk River depositional system and examines the relative control of lithofacies on sites of gas accumulation. This summary represents work in progress on the sequence stratigraphic characterization of the Milk River Formation.

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2. Regional Stratigraphy

The Santonian-Campanian Milk River Formation in Canada and its regionally correlative Eagle Sandstone in Montana (Figure 2) form the basal part of the Montana Group. The Milk River is composed of three members, from base to top, the Telegraph Creek Member, the Virgelle Member, and the Deadhorse Coulee Member. The Virgelle is often informally subdivided into a lower and upper part; the boundary is placed where a pronounced change in depositional environment is evident. In Montana, the correlative Eagle Sandstone is subdivided into the Virgelle Member and unnamed rock units of alluvial origin. The Telegraph Creek is placed stratigraphically below the Eagle. In both Canada and north-central Montana, the base of the Telegraph Creek is placed at the top of the Niobrara Formation of the Colorado Group. The Niobrara Formation is a calcareous, coccolithic-bearing shale and thus, in core, the top of the formation is an excellent marker horizon separating rocks of the Montana Group from those of the Colorado Group. The Milk River is overlain by the Pakowki Formation and the Eagle Sandstone is overlain by the Claggett Shale (Figure 2). The Ardmore bentonite beds, found in the lower part of the Pakowki and Claggett, provide an excellent upper marker unit. Thus, the two lithologic markers can be used to provide boundaries to the Milk River Formation depositional system.

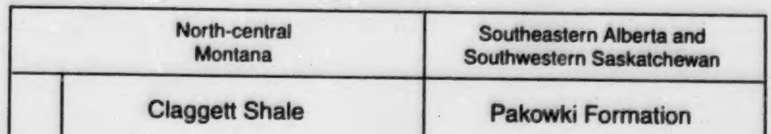

Figure 2 - Stratigraphic chart showing correlation of members of the Milk River Formation, Alderson Member of the Lea Park Formation, Saskatchewan and Alberta, Canada, and members of the Eagle Sandstone, Montana, U.S.A.

In Montana, rocks assigned to the Virgelle Member are, in part, older than those assigned to the Virgelle in Canada. The Milk River and Eagle have generally been considered to represent a mainly progradational, wave-dominated depositional system within the Cretaceous Interior seaway of North America. The Virgelle in Canada represents the later part of the main seaward-stepping progradational event and is correlative to the wedge of marine sandstone in the middle part of the Eagle (Gill and Cobban, 1973, p16).

3. Previous Studies

The principal study area for the current investigation is between longitude 108° and 113° and latitude 49° and 51° in southwestern Saskatchewan and southeastern Alberta. Within this area, only a few detailed facies architecture studies of the Milk River Formation have been made (limited to Alberta). Outcrops of the Milk River Formation are confined to the vicinity of the Writing-on-Stone Provincial

Park, Alberta, (Figure 1) where the Milk River has dissected outcrops of this rock unit, providing excellent three-dimensional exposures for stratigraphic and sedimentologic analysis. Three detailed studies of these exposures have resulted in three slightly different interpretations of the origins of the formation (McCrory and Walker, 1986; Cheel and Leckie, 1990; Meyer *et al.*, 1998). Each of the studies interpreted the Telegraph Creek to have been deposited in the offshore-transition zone below shoreface sands of the lower part of the Virgelle Member. All three studies subdivided the Virgelle Member into an upper and lower part based on a distinct paleodepositional environment break. The lower part of the Virgelle was interpreted to have been deposited primarily as lower shoreface to middle shoreface sands along a wave-dominated coastline. The upper part was interpreted to have been deposited in a complex tidal setting. The models for the tidal processes vary somewhat between the three reports. The tidal complex models will not be reviewed here because the link between these outcrop facies and the subsurface facies in the distal offshore has not been completed. All three studies of the Milk River outcrops interpret the Deadhorse Coulee Member (Figure 2) to have been deposited in fluvial-alluvial plain environments.

Principal published subsurface characterizations of the Milk River Formation are limited to studies by Meijer-Drees (1972) and Meijer-Drees and Myhr (1981). In cross-sections, the succession of facies (discussed above) was shown to change laterally down dip to the north into fine-grained facies. The upward succession of these facies was divided into offshore, subtidal, nearshore, and intertidal and subtidal. These facies were interpreted from core from the ARCO Alderson well 10-14-15-10W4 (Figure 1) and were calibrated to wireline logs. From their subsurface studies, Meijer-Drees and Myhr (1981) plotted the depositional extent of shoreface sandstone in the Virgelle. The sandstone trends northwest-southeast (Figure 1), and is believed to approximate the orientation of Milk River Formation shorelines in Alberta and Saskatchewan. Where the facies that characterize the Virgelle and Deadhorse Coulee members are no longer recognizable (i.e. they pass laterally into fine-grained facies), the stratigraphic succession has been redefined as the Alderson Member of the Lea Park Formation (Figure 2) (Meijer-Drees and Myhr, 1981). Detailed information on the Milk River sedimentology is not reviewed here, but where appropriate has been incorporated into the discussion of the facies determined along the two transects described in this paper. Facies reported herein are for the Alderson Member of the Lea Park Formation, although this terminology has not been universally adopted as a replacement for the Milk River Formation or Milk River equivalents. For the purposes of this report, the discussion refers to this stratigraphic succession as the Milk River Formation.

4. Methods

Most of the Milk River Formation occurs in the subsurface. The formation is characterized by low-contrast response on wireline logs due to the shaly nature of the rocks throughout much of the depositional system. Detailed observations of selected cores, logged at a scale of 0.3 m (one ft), from Saskatchewan and Alberta have been used to calibrate wireline log responses to depositional facies. Principal observations included sedimentary structures, lithologies, trace fossil and macrofossil assemblages, and major diagenetic changes (mostly the presence of siderite and glauconite). Preliminary results of the detailed description of the Milk River are presented in two strike-oriented cross-sections through the main part of the Milk River gas field (Figures 3 and 4). The detailed observations permit lateral correlation of lithofacies and of significant erosion surfaces between wells, and serve as a basis for evaluation of gas productive facies. The datum used in the cross-sections is a prominent bentonite bed in the lower part of the Pakowki Formation.

5. Lithofacies Architecture

Seven distinct lithofacies and their preliminary inferred depositional environments are summarized below and are shown on Figures 3 and 4. One additional facies that is thought to be present is not described because no representative core has been examined. This facies is designated as F? and occurs only at the base of the Milk River Formation in well 6 (Figure 3). It could represent fluvial rocks. Siderite is locally present throughout all lithofacies except I and II. Its position within the described sections on Figures 3 and 4 is not shown except where it occurs at erosional surfaces. Likewise, nondescript burrows and areas of bioturbation are not shown on Figures 3 and 4 because they are pervasive throughout all lithofacies. The discussions of the lithofacies below are listed from deeper to shallower water environments.

I: Offshore Facies

This facies is dominated by calcareous, coccolithic mudstone (>90 percent) that is interbedded with thin (millimetre scale) siltstone. This facies coincides with the upper part of the Niobrara Formation. Strata in this facies were deposited below storm wave base.

II: Offshore-Transition Facies

Mudstones and siltstones of the offshore facies grade vertically into centimetre- to decimetre-thick, very fine-grained sandstone that is interbedded with siltstone and mudstone. The mudstone and overlying sandstone form vertically stacked couplets within which both the proportion and thickness of the sandstone interbeds increase and the intervening siltstone and mudstone beds decrease in thickness upwards through this facies. The sandstones have sharp bases and tops. In the lower part of this facies, they are relatively clay rich and are commonly parallel laminated. In the upper part, they typically exhibit hummocky cross-stratification. The top of this facies is generally characterized by thick (metre-scale) amalgamated, hummocky cross-stratified sandstone

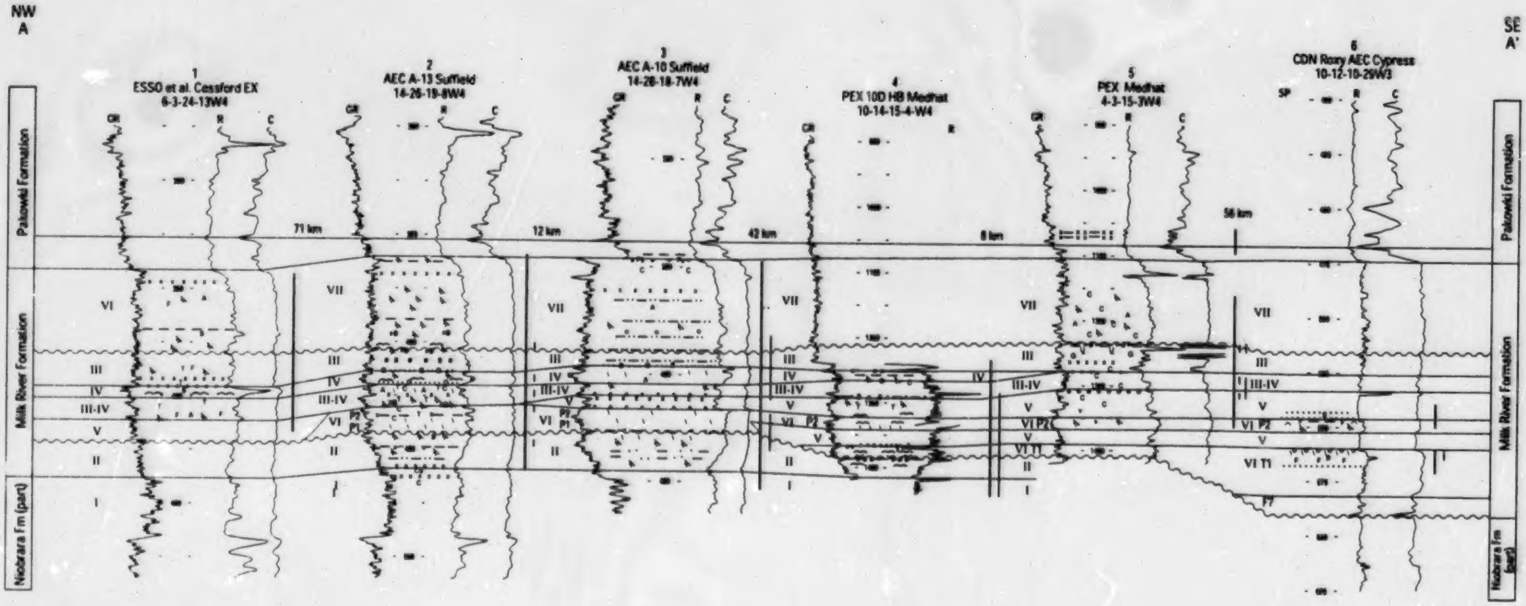

Figure 3 - Cross-section A-A', showing correlation of lithofacies I to VII, and simplified sedimentary structures in the Milk River Formation. Tested and cored intervals shown to the right of each well. Depths for wells 1 to 3 and 6 are in metres. Depths for wells 4 and 5 are in feet. Locations of wells are shown in Figure 1. (Gr, gamma ray; R, resistivity; C, conductivity; and SP, spontaneous potential). Explanation of symbols is shown on Figure 4.

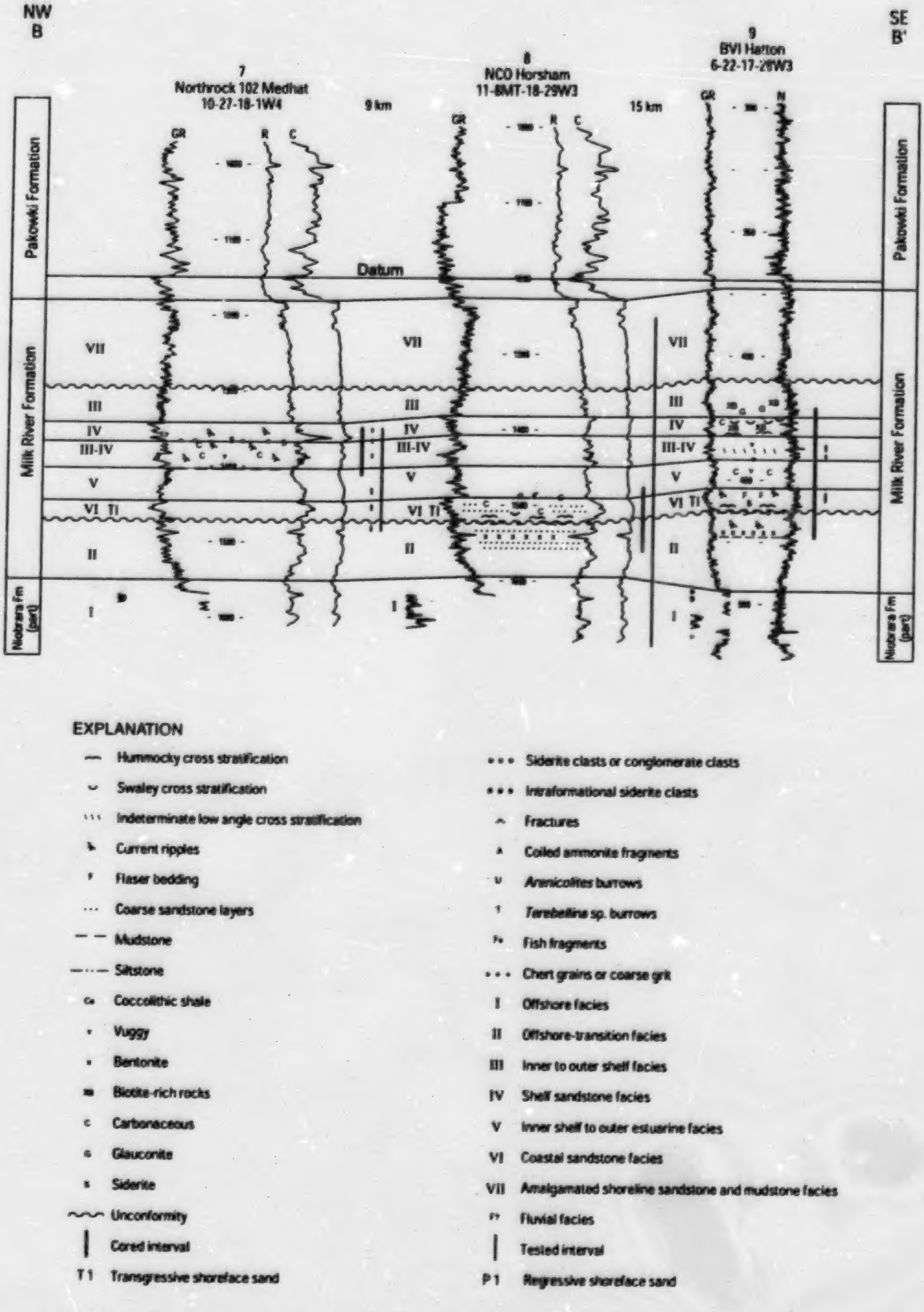
NW
B
SE
B'
7
Northrock 102 Medhat
10-27-18-1W4
9 km
8
NCO Horsham
11-8MT-18-29W3
15 km
9
BVI Hatton
6-22-17-28W3
GR
R
C
N
Datum
Pakowki Formation
Milk River Formation
Niobrara Fm (part)
VII
III
IV
III-IV
V
VI TI
II
I
EXPLANATION
Hummocky cross stratification
Swaley cross stratification
Indeterminate low angle cross stratification
Current ripples
Flaser bedding
Coarse sandstone layers
Mudstone
Siltstone
Coccolithic shale
Vuggy
Bentonite
Biotite-rich rocks
Carbonaceous
Glauconite
Siderite
Unconformity
Cored interval
T1 Transgressive shoreface sand
Siderite clasts or conglomerate clasts
Intraformational siderite clasts
Fractures
Coiled ammonite fragments
Arenicolites burrows
Terebellina sp. burrows
Fish fragments
Chert grains or coarse grit
I Offshore facies
II Offshore-transition facies
III Inner to outer shelf facies
IV Shelf sandstone facies
V Inner shelf to outer estuarine facies
VI Coastal sandstone facies
VII Amalgamated shoreline sandstone and mudstone facies
Fluvial facies
Tested interval
P1 Regressive shoreface sand

Figure 4 - Cross-section B-B', showing correlation of lithofacies I to VII, and simplified sedimentary structures in the Milk River Formation. Tested and cored intervals shown to the right of each well. Depths for wells 7 and 8 are in feet. Depths for well 9 are in metres. Locations of wells are shown in Figure 1. (Gr, gamma ray; R, resistivity; C, conductivity; and N, neutron).

that is commonly current rippled at the top. No distinct trace fossil assemblages were observed. Bioturbation is locally pronounced with many thinner sandstone beds intensely to thoroughly bioturbated. Deposition of this facies is interpreted to have taken place under alternating storm and quiet-water conditions between fair-weather and storm wave base (Howard and Reineck, 1981; Dott and Bourgeois, 1982).

III: Inner to Outer Shelf Facies

This facies is characterized by very fine- to fine-grained sandstone with some coarse-grained sandstone and grit layers. The topmost sandstones are locally very glauconitic (as pellets) and contain abundant green-grey clay clasts and mud drapes. Flat and current ripple laminations are the dominant sedimentary structures. Maximum thickness of this interval is 9 m; the most glauconitic sandstone, which is at the top of this facies, is commonly less than 0.2 m thick. The sandstones are locally bioturbated; *Terebellina* burrows were observed in one core. Ammonite fragments and indeterminate coiled specimens have been found in this interval from the lowermost current ripple-laminated to low-angle cross-bedded sandstone. Strata in this facies are interpreted to have been deposited in inner to outer shelf, shallow-water environments as required for the development and preservation of the glauconite (Stonecipher, 1997). Glauconite typically develops in areas of low sediment input in the inner to outer shelf. High concentrations of glauconite pellets such as those observed in the cores form through winnowing under shallow-water, non-oxidizing conditions. The presence of the coiled ammonites suggest water depths somewhat deeper than those of the middle shoreface.

IV: Shelf Sandstone Facies

This sandstone facies is superficially similar to the coastal sandstone facies described below. The sandstones tend to be clean, although carbonaceous material is locally present at the top or base of the sandstone. Sedimentary structures include hummocky or swaley cross-stratification that is overlain by ripple laminations. Coiled ammonite fragments have been found at the base of the shelf sandstone in well 3 (Figure 3). The sandstones are bounded by mudstone that commonly contains glauconite. The vertical succession of sedimentary structures and the apparent encasement of the sandstones in marine siltstones and mudstones, some of which are glauconitic, suggest that this facies was deposited as shelf sandstone. This facies is interbedded with the inner to outer shelf facies and may form stacked sequences as much as 12 m thick.

V: Inner Shelf to Outer Estuarine Facies

This heterolithic facies is characterized by interbedded very fine-grained sandstone, siltstone, and mudstone of centimetre to decimetre to metre thickness. There is no upward thickening of the sandstone-mudstone beds to form couplets like those observed in the offshore-transition facies. Shell fragments, unidentified pelecypods, and fragments of *Baculites* sp. are scattered throughout the facies. The facies is commonly very carbonaceous. Ripple and flat laminations are the most prominent sedimentary structures, although flaser bedding is locally well developed. The base of this facies may be marked by a thin (<3 m thick) hummocky cross-stratified sandstone. Bioturbation is locally intense, commonly destroying sedimentary structures. Burrows, most prominently *Terebellina*, are abundant. The interbedded, relatively flat nature of the sandstone and mudstone units that show no preferred upward thickening of sandstone-mudstone couplets suggests tidal influence (Greb and Archer, 1998; Adkins and Eriksson, 1998). The preservation of shelly fauna suggests a somewhat quieter depositional setting than that observed for a storm-dominated coastal setting. Although its lateral relationships have not been fully determined, this facies appears to lie lateral to the coastal shoreface sandstones of lithofacies VI as well as overlie them. It is provisionally interpreted to have been deposited in the distal end of estuaries where there was interaction between tidal and inner shelf processes.

VI: Coastal Shoreface Sandstone Facies

Lithofacies II, the offshore-transition facies, is overlain by thick (up to 15 m), very fine- to medium-grained sandstone. In vertical succession, from the base to the top, sedimentary structures consist of poorly preserved low-angle cross-stratification, swaley cross-stratification, and current ripple or flat laminations. Bioturbation, mostly *Terebellina* burrows, is randomly distributed within this facies, but is most intensely developed in the upper current-rippled and laminated sandstone. Although carbonaceous material is found throughout the facies, it is most concentrated in the upper few metres. The vertical succession of sedimentary structures is similar to that found in the middle to lower shoreface sandstones and to that described from the lower Virgelle (McCrory and Walker, 1986; Meyer *et al.*, 1998) at Writing-on-Stone Provincial Park. *Terebellina* burrows are thought to occur in shoreface to nearshore (shoreface toe) depositional environments (Chamberlain, 1978). Meyer *et al.* (1998, Table 1) reported the presence of *Terebellina* in their middle shoreface facies. Preserved fossils are generally lacking due to the high energy within the depositional environments. Strata are provisionally interpreted to have been deposited between fair weather base and mean low water in a high-energy, storm-dominated nearshore environment.

VII: Amalgamated Shoreline Sandstone and Mudstone Facies

This facies, which is up to 42 m thick, is an amalgamation of stacked fine-, to very fine-grained, clean to muddy sandstone beds deposited in channels of undetermined size. The basal sandstone tends to be coarser grained (fine size range) than sandstone (very fine size range) of the underlying facies. Where they occur, mudstone layers and drapes are most common in the upper parts of individual channel sandstones. Rarely, black mudstone caps sandstone units. The sandstones are carbonaceous, and locally contain woody fragments where they occur at the base of a channel. The sandstones are dominantly flat to ripple laminated. Bioturbation is locally intense. Shell fragments, unidentified pelecypods, and large baculitids and coiled ammonite fragments are common throughout. Gastropods have been observed in the upper part of this facies. This unit is widespread in the subsurface (Gilboy, 1996); however, it is not observed at the outcrop at Writing-on-Stone Provincial Park. The base of the unit, as determined in the two cross-sections, is undulatory. It cuts into the underlying inner to outer shelf facies. Although additional work is needed to determine fully the spatial geometry of this facies and hence its depositional environment, these sandstones and thin mudstones are believed to be the result of deltaic deposition with their geometry modified by coastal longshore or storm processes to form sheetlike bodies. Similar thick, stacked sandstones in the middle Eagle Sandstone, Montana, were interpreted by Rice and Shurr (1983) to represent deposition by deltaic processes. Neither rooting nor bleaching of the top sandstones in this facies was observed. The top of this facies, which represents the top of the Milk River Formation, is overlain unconformably by the Pakowki Formation. Grit, black chert pebbles, and concentration of fish fragments mark the contact between the Milk River and Pakowki.

6. Discussion

The vertical stacking of the lithofacies shown in cross-section A-A' (Figure 3) and B-B; (Figure 4) describes a different model for deposition of the Milk River than is commonly proposed. Two major erosional surfaces have been recognized. When tied to unpublished dip-oriented cross-sections, each suggests a drop in sea level, a basinward shift in facies, and creation of accommodation space during the ensuing sea-level rise. This accommodation space appears to have been greater in Saskatchewan, where the Milk River thickens (well 6, Figure 3). The controls for this shift are unknown, but are speculated to be related to tectonic activity to the southwest. The basal erosion surface cuts out parts of the Telegraph Creek (lithofacies II). In several of the cores, this surface is marked by a transgressive lag consisting of black, red, and tan cherts along with angular to subangular rock fragments of undetermined composition (Figures 5A and 5B). The configuration of this surface has not been fully determined but, based on work in progress, beveling of the Telegraph Creek appears to increase irregularly to the southeast, east of the South Saskatchewan River. The Milk River is thicker in cross-section B-B' than it is in A-A'; the difference in thickness is attributed to differential subsidence. The upper erosional surface occurs between the amalgamated shoreline sandstone and mudstone facies and the inner to outer shelf facies. This surface is, in places, marked by a lag consisting of siderite clasts set in green-grey clay matrix (Figure 5C).

The type of lithofacies that overlies the basal erosional surface varies depending on the position of the facies on the incised surface. The juxtaposition of facies of shallower water origin deposited after a sea-level fall to deeper water facies deposited during a previous regression suggests that the basal erosional unconformity that separates these facies represents a sequence boundary. The deepest incision by the unconformity occurs in well 6 (Figure 3). Here, the unconformity is overlain by an undefined unit (no cores through this unit have been examined, but its log response indicates that it could possibly be of fluvial origin). The overlying facies have sedimentary characteristics of shoreface sands and are interpreted to represent lowstand or transgressive shoreface deposits (VI T1). The vertical stacking of facies of the fluvial and overlying shoreface sandstone is indicative of marine lowstand to transgressive deposits filling an incised valley.

The coastal shoreface sandstone facies (VI T1) in well 6 (Figure 3) is overlain by inner shelf to outer estuarine facies (V) that pinch out laterally into a stacked sandstone sequence (VI) that is interpreted to represent younger shoreface sandstones of two progradational events (VI P1 and VI P2). Both upper shoreface sandstones (VI P1 and VI P2) wedge out between A-A' and B-B', and shoreface sandstone VI P2 thins to the southeast. These shoreface sandstones are laterally replaced and in some cases overlain by a thinly laminated sandstone-mudstone sequence of the inner shelf to outer estuarine facies (V). The lateral cut-out of the shoreface sandstones and infill of the erosional surfaces by inner shelf to outer estuarine facies are similar to the situation observed in offshore sand bodies in the Gulf of Lions in the western Mediterranean (Berne *et al.*, 1998), interpreted to represent prograding shoreface sands deposited during a forced regression. The coastal shoreface sandstone (VI P1 and VI P2) and inner shelf to outer estuarine facies (V) represent marine regression.

Overlying the regressive succession of facies is another transgressive sequence represented by mixed inner to outer shelf facies and shelf sandstone (III and IV), shelf sandstone facies (IV), and an overlying outer shelf facies (III). The base of this transgressive package of rocks in many of the cores is defined by a reworked zone of siderite clasts (Figure 5D). The outer shelf facies (III) of the transgressive succession is glauconitic and, in several cores, a coarse grit, siderite concretion and pebble lag set in green-grey clay matrix (Figures 5E and 5F) and glauconitic sandstone occur at the contact with the underlying shelf sandstone facies (IV). The coarse interval represents a transgressive lag as the deeper water outer shelf units migrated landward over the shelf sandstone, which may have built up into the fair weather base zone.

The outer shelf facies (III) is erosionally overlain by the amalgamated shoreline sandstone and mudstone facies (VII). The configuration of this incised surface is unknown, but from reconnaissance studies and published cross-sections (Meijer-Drees, 1972; Meijer-Drees and Myhr, 1981; Gilboy, 1996), the depth of incision is considerably less than that observed for the lower erosional surface. The relationship of this facies to outcrop units of the Milk River Formation has not

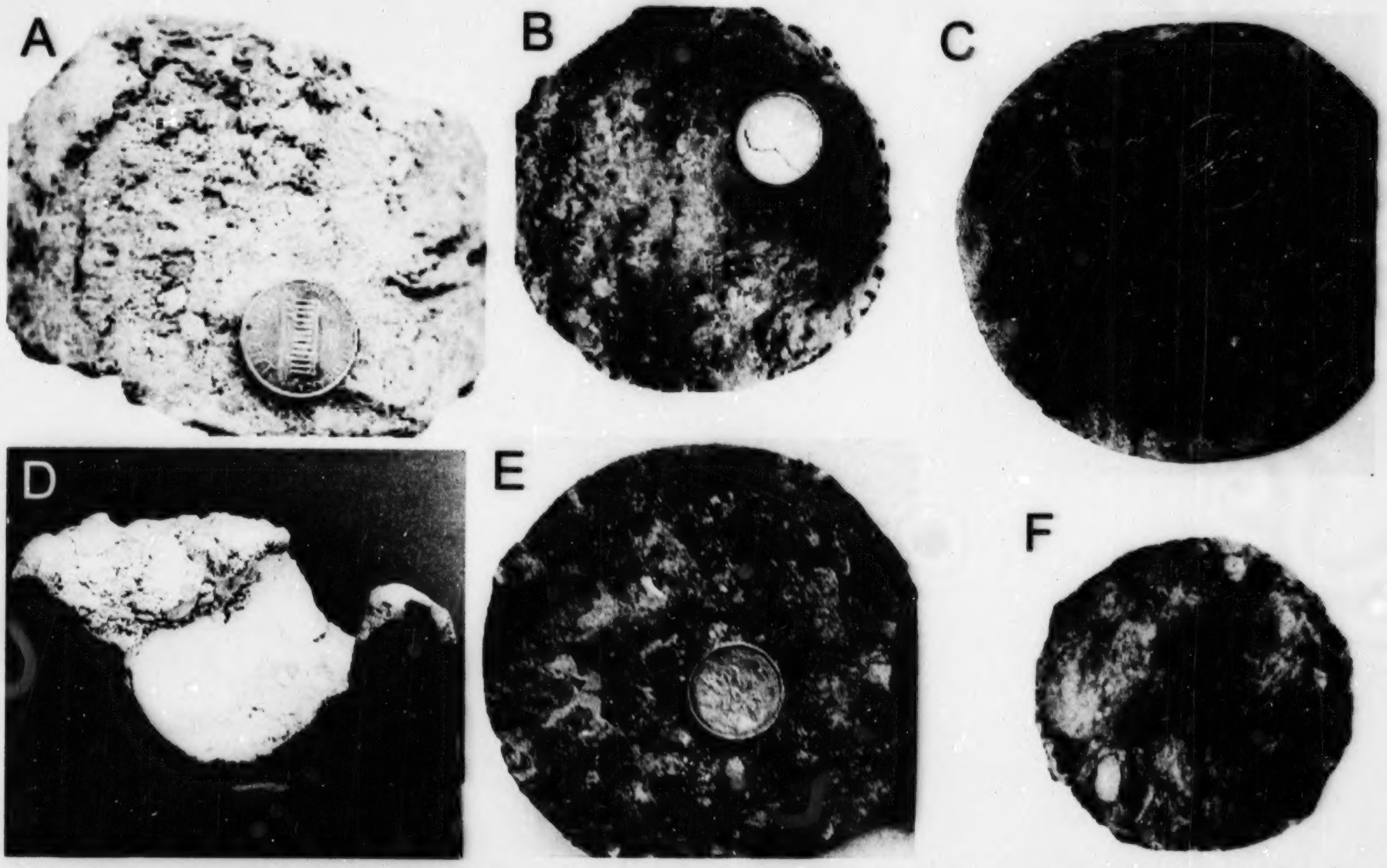

Figure 5 - Photographs of conglomerates in the Milk River Formation, Alberta and Saskatchewan. A) Conglomerate from 463.3 m (1520 ft) depth, NCO Horsham 11-8-18-29W3 well. Clasts consist of tan, red, and black angular to subangular chert pebbles up to 1.5 cm long. Conglomerate zone is 15 cm thick. B) Siderite-cemented clast conglomerate from 460 m depth BVI Hatton 6-22-17-28W3 well. Clasts consist of red and black chert, quartz, and green(?) pebbles, and rock fragments up to 0.6 cm long set in a grey-green clay matrix. C) Siderite-cemented clast conglomerate from 374.5 m (1228.6 ft) depth, PEX Medhat 4-3MR-15-3W4 well. Clasts are black chert and clear quartz pebbles up to 2.5 cm long and are set in green-grey clay matrix. D) Siderite-cemented clast conglomerate from 391.7 m (1285 ft) depth, PEX IOD HB Medhat 10-14MR-15-4W4 well. Clasts are black and cream siderite nodules up to 1.3 cm long and are set in green-grey clay matrix. E) Conglomerate from 391.3 m (1283.9 ft) depth, PEX Medhat 4-3MR-15-3W4 well. Clasts are black and tan chert pebbles, indeterminate subangular rock fragments up to 1.2 cm long and are set in a green-grey clay matrix. F) Siderite-cemented intraclast conglomerate from 413.3 m (1356 ft) depth, Northrock 102 Medhat 10-27-18-1W4 well. Clasts are siderite nodules or small concretions up to 20 cm in length. Coins are approximately 1.8 cm diameter.

been determined; however, this facies may form the basal transgressive unit of the Pakowki transgression. Lag deposits between the Pakowki and Milk River may represent a transgressive surface of erosion.

O'Connell *et al.* (1999) also recognized the presence of two erosional (sequence) boundaries, but it is not clear how their boundaries conform to those discussed above, especially in the manner in which they tie the boundaries to the Milk River outcrop succession. They suggested that the Alderson Member is depositionally unrelated to the Milk River succession observed in outcrop and that the member rests on a third-order sequence boundary. The depositional models suggested by this study and by O'Connell *et al.* (1999) indicate that additional work needs to be done on the Milk River depositional system. Redefinition of the facies relationships through analysis of vertical stacking sequences can provide predictive models for the best targets for gas accumulation.

7. Age Relationships

An understanding of the age relationships of the units comprising the Milk River Formation is an important component of the sequence stratigraphic modelling. The age of the Milk River is commonly thought to span the Santonian-Campanian boundary, based on its correlation to the Eagle Sandstone in Montana. Dating of the Eagle has been based on ammonite zones (Gill and Cobban, 1973); however, datable ammonite specimens from the Milk River are lacking. An upper age limit to the Milk River of 80.71 Ma is based on $^{40}Ar/^{39}Ar$ dating of sanidine in the Ardmore bentonite (Hicks *et al.*, 1995). This bentonite (actually a series of bentonites) occurs in the lower part of the Pakowki and its correlative Claggett Shale in Montana and is a widespread regional marker unit. Two bentonites in the Ardmore unit in well 5 (Figure 3) provide calibration of the bentonite markers to wireline log responses. There are scattered bentonites in the Milk River Formation, some of which can be correlated between wells as discrete bentonites or as biotite-rich sandstone or mudstone beds. None of these bentonites has been dated. As part of this project, several bentonites of the Milk River were collected for age dating; however, no sample has contained sanidine suitable for the argon-argon laser fusion dating method (Obradovich, 1993). One bentonite sample from the upper part of the Eagle Sandstone in the Elk Basin, Wyoming, yielded a $^{40}Ar/^{39}Ar$ date of 81.14 ±0.51 Ma, but it is unknown how this bentonite correlates within the Milk River (Hicks *et al.*, 1995).

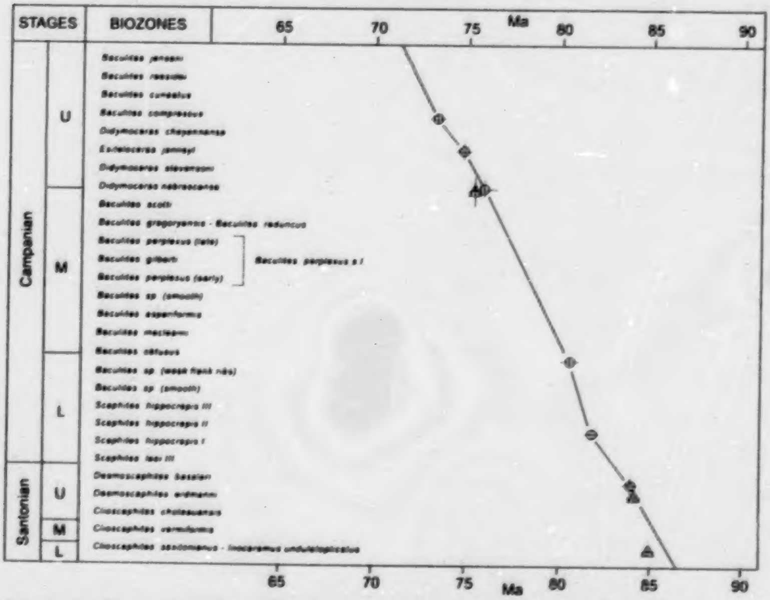

Figure 6 - Biostratigraphic chart showing ammonite zonation and their relative ages based on $^{40}Ar/^{39}Ar$ radiometric dates of sanidine from bentonites (from Obradovich, 1993).

Ammonites have been used to subdivide the Montana Group into incremental time zones (Gill and Cobban, 1973) which, where possible, have been tied to $^{40}Ar/^{39}Ar$ radiometric dates of sanidine from bentonites. The Santonian-Campanian boundary has been dated at 83.5 ±0.5 Ma, which occurs between the *Desmoscaphites bassleri* and *Scaphites leei* III ammonite zones (Figure 6). The top of the Milk River Formation and the correlative Eagle Sandstone is within the *Baculites* sp. (smooth) or *Baculites* sp. (weak flank ribs) zones. Ammonites collected from Milk River core included two that could be identified with some certainty (W.A. Cobban, pers. comm., 2000). Numerous large (up to 4 cm wide by 12 cm long), smooth-shelled baculitids are present in several cores in the amalgamated shoreline sandstone and mudstone facies (Figure 7A). They have been identified as *Baculites* sp. (smooth) (W.A. Cobban, pers. comm., 2000) and are characterized by simple sutures and lack flank rib ornamentation. In the upper part of the amalgamated shoreline sandstone and mudstone facies (VII), these large smooth-shelled baculitids are also associated with large baculitids showing some weak flank ribs, but specimen preservation was too poor to permit identification.

Coiled ammonites have also been observed in several cores from the inner to outer shelf facies (III) and from the amalgamated shoreline sandstone and mudstone facies (VII). Preservation of most is too poor to permit identification. However, one specimen (Figure 7B) at 424.39 m in the inner to outer shelf facies, below the amalgamated shoreline sandstone

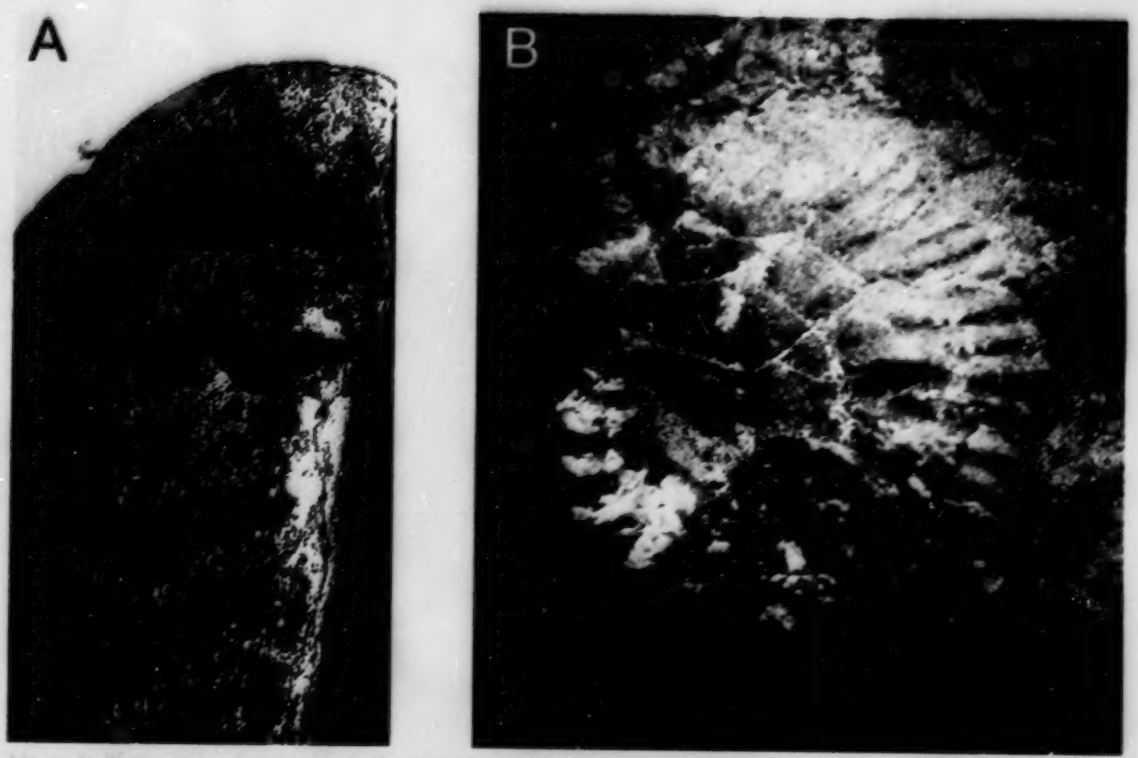

Figure 7 - Photographs of ammonites in the Milk River Formation, Saskatchewan. A) *Baculites* sp. ***(smooth) from 721.17 m depth in the Seagull Staynor Hall 6-27-1-23W3 well . Note the simple suture pattern. Ammonite is 10.1 cm long by 3.05 cm wide. B)*** *Scaphites hippocrepis* sp. ***from 424.39 m depth in the Antelope et al. Smiley 12-28-30-25W3 well. Ammonite is 3.8 cm high by 3.3 cm wide. Identifications provided by W.A. Cobban, U.S. Geological Survey.***

and mudstone facies, in the Antelope et al. Smiley 12-28-30-25W3 well has been identified as a *Scaphites hippocrepis* sp. (W.A. Cobban, pers. comm., 2000), but the exact species (I, II, or III) could not be determined.

In general, age-diagnostic palynomorphs from the Milk River are lacking. Palynomorph assemblages have been reported from two intervals in the City of Medicine Hat Hatton 8-15-16-28W3 well (Gilboy and Nambudiri, 1991). The lower sample at 500.3 m is from the lowest part of the inner shelf to outer estuarine facies (V) of this report. Lack of characteristic index species from this sample prevented age and depositional environment interpretation. The upper sample at 436.61 m is from the amalgamated shoreline sandstone and mudstone facies (VII) of this report. The lithofacies described from this interval (Gilboy and Nambudiri, 1991; this study) is similar to that of the amalgamated shoreline sandstone and mudstone facies shown on the two cross-sections. The palynomorph assemblage indicated a Campanian age, which is in agreement with the *Baculites* sp. (smooth) fossils found in this lithofacies in other core.

Magnetostratigraphic dating of the Pakowki and Milk River has resulted in an equivocal age for the Milk River Formation when the results are interpreted within the context of ammonite and foraminiferal zones (Leahy and Lerbekmo, 1995). The contact of polarity chron 33r-34n is placed within the Deadhorse Coulee, approximately 38 m above the contact with the Virgelle Member. This part of the Deadhorse Coulee was correlated to the middle and upper members of the Eagle Sandstone in Montana by Meijer-Drees and Myhr (1981). As such, the base of the polarity chron 33r should be somewhere within the *Scaphites hippocrepis* III and the *Baculites* sp. (weak flank ribs) zones. Leahy and Lerbekmo (1995) placed the base of the chron 33r within the lower part of the *Baculites* sp. (smooth) zone, which would make the contact between the 33r-34n in the Campanian. This age assignment is, however, at odds with magnetostratigraphic results in Europe where the Santonian-Campanian boundary is placed in the lower part of chron 33r (Perchersky *et al.*, 1983). These inconsistencies indicate that the Milk River has a much more complex depositional history including the possible presence of internal sequence boundaries (O'Connell *et al.*, 1999) than has been previously recognized. Until the complex facies relationships are completely worked out within a sequence stratigraphic context, the relationship of the polarity chron 33r-34n contact to the ammonite zones is in flux.

8. Gas Production

The Milk River Formation is the most underexplored of the three formations that characterize the southeast Alberta gas field (Figure 1). Currently all gas production is assigned to the Alderson Member of the Lea Park Formation; however, for discussion purposes, the term Milk River will be used to refer to the gas-bearing strata. Table 1 summarizes information on lithofacies, tested zones, initial production where available, drillstem tests, and current status of the wells shown in cross-sections A-A' and B-B'. The tested intervals are also shown on the two cross-sections (Figures 3 and 4). In many instances, because multiple zones within the Milk River were tested, it is impossible to tell which intervals are actually productive. In addition, other formations such as the Medicine Hat and the Belle Fourche (drillers' Second White Specks) are often tested at the same time and production is not always isolated to a particular formation. This makes it difficult to assess the actual productive potential and productive facies of the Milk River Formation.

In cross-sections A-A' and B-B', the main zones tested are within the inner to outer shelf facies (III), shelf sandstone facies (IV), and coastal sandstone facies (VI). On the wireline logs, targets appear to be the thin, cleaner looking sandstones that are interbedded with sandstones that are quite clay rich or are overlain and underlain by mudstone units. In the gas-bearing interval, some of the sandstones examined in core are very friable and vuggy (shown in Figures 3 and 4) indicating a lack of cementation. Both the clean and clay-rich sandstones are often carbonaceous, contain finely comminuted organic matter, and can have good porosities (12 to 20 percent) (Meijer-Drees, 1972; unpublished data this study). RockEval analyses of some of these sandstones (not the shales) indicate a total organic carbon content from 0.4 to 1.5 percent, although the average is from 0.4 to 0.6 percent. This low level of organic matter content is believed to be sufficient for generation of biogenic gas; only 0.5 percent is thought to be required (Clayton, 1992). Only wells 2 and 3 on cross-section A-A' (Figure 3) tested the amalgamated shoreline sandstone and mudstone facies (VII) of the Milk River. The productive potential of this facies has not been adequately tested. The amalgamated shoreline sandstone and mudstone facies (VII) is gas productive in some wells in the Medicine Hat area (Meijer-Drees, 1972), but the most productive facies at that location are in the inner shelf to outer shelf (III) and shelf sandstone facies (IV) described in this report. The lack of gas productivity in the amalgamated shoreline sandstone and mudstone facies (VII) may reflect the general lack of interbedded carbonaceous mudstones which are thought to be the main source for the gas (Meijer-Drees, 1972).

Figure 8 shows the main gas producing area in the Milk River Formation and areas where Milk River and Medicine Hat gas is commingled. This production appears to be disconnected from the seaward pinch out of the sands that define the Virgelle Member (Figures 8A and 8B). However, along the west margin of the current gas field on a line between Brooks and Medicine Hat, many of the productive wells produce water, suggesting at least some link to the updip recharge area to the south and southwest. The current extent of the Milk River gas field might simply reflect past drilling practices, having grown by step-out drilling from productive single completion wells. Some of the scattered wells, which have been tested between the main gas field and the Virgelle sandstone pinchout, do contain gas (Meijer-Drees, 1972); however, the current practice of testing only a few thin, isolated sandstone beds, based on their geophysical log characteristics, suggests that pay zones may have been overlooked. The shaly nature of the rocks (this study; Meijer-Drees and Myhr, 1981) also suggests that wireline log responses may not adequately reflect the presence of gas. Subsurface cross-sections (Meijer-Drees, 1972; Meijer-Drees and Myhr, 1981; unpublished sections this study) indicate that facies similar to those described herein extend updip to the south.

Gas production in the Milk River does not appear to be solely controlled by orientation of depositional facies. The trend of production occurs at an oblique angle to the inferred northwest-southeast-trending shoreline as suggested by the depositional limit of the Virgelle Sandstone. O'Connell *et al.* (1999) suggest that: a) the gas in the Alderson Member was trapped in offshore sandstones encased in shelf mudstones above a third-order sequence boundary, and b) this sequence boundary provided a discontinuity between these units and the shoreline sandstones of the Milk River, thus preventing the gas from migrating updip. Although two sequence boundaries or principal erosion surfaces may be present within the Milk River, the boundary itself is not the barrier to gas migration. The nature of the various lithofacies comprising the Milk River and their lateral and vertical juxtaposition in relation to the depth of incision of the erosional surfaces will determine the extent of gas accumulation, gas migration, and hydrologic connectivity. Thinly bedded sandstones are not necessarily impervious to gas or water migration. Hydrologic models that will examine the connectivity of groundwater flow in the outcrop succession of the Milk River to adjacent lithofacies that rest on the erosional surfaces in the subsurface are required before the extent of gas and water migration is known. Modeling should focus on the time of gas exsolution and migration and not on the present-day hydrologic regime.

Drilling may ultimately extend the Milk River gas field to the south (based on similarity of facies) modifying its current configuration. However, another control on the current position of the gas field should also be considered. This is the relationship of the position of the most favourable facies (inner to outer shelf (III), shelf sandstones (IV), and the coastal sandstones (VI) described in this report) in the Milk River Formation to the part of the Sweetgrass Arch where the structure contours flatten. The Sweetgrass Arch, a periodically active structure, achieved its present configuration during the Laramide orogeny (Thomas, 1974, 1979;

Table 1 - Lithofacies, tested zones, initial production (or average daily production during first year when initial production is not available), drillstem test interval and results, and current status of wells listed in cross-sections A-A' and B-B'. Lithofacies tested are listed from top to bottom in the well. (IP), initial production; (F), average daily production during first year; (C), commingled average daily production during first year. Test intervals of wells A4, A5, B1, and B2 shown in feet and A1 to A3, A6;and B3 in metres. Producing = production from Milk River; Standing = well completed, cased, and ready for production. Data are from a database leased from Datashare International, Inc. and are current through June 1996.

Well	Cross-section Location	Lithofacies	Tested Interval	Initial Production $10^3 m^3/d$	Drillstem Test Interval and Results	Current Status
Esso et al. Cessford EX 6-3MH-24-13W4	A 1		Not tested		No Data	Produces from Medicine Hat
AEC A-13 Suffield 14-26-19-8W4	A 2	VII IV III-IV VI P1 P2	403.0 - 404.0 415.6 - 417.6 424.0 - 425.0 431.9 - 433.0 448.5 - 449.5	1.12 (F)	416.0 - 416.1 416.0 - 416.1 416.5 - 416.5 417.6 - 417.6 426.7 - 426.7 431.3 - 431.3 No Results	Producing
AEC A-10 Suffield 14-28-18-7W4	A 3	VII III IV III-IV VI P1 P2 II	379.1 - 379.6 380.3 - 381.0 390.8 - 391.4 393.7 - 394.1 400.4 - 402.8 404.4 - 405.0 407.6 - 408.4 409.1 - 410.0 416.8 - 419.0 420.1 - 421.5 422.3 - 423.0 429.2 - 429.7 432.5 - 433.4	4.40 (IP)	No Data	Producing
PEX IOD HB Medhat 10-14MR-15-4W4	A 4	III-IV V VIP2 II I	1290.0 - 1450.1	2.12 (F)	No Data	Producing
PEX Medhat 4-3MR-15-3W4	A 5	III III-IV V	1237.9 - 1248.0 1337.9 - 1341.9 1354.0 - 1359.9 1337.9 - 1359.9	3.74 (F)		Producing
CDN Roxy AEC Cypress 10-12-10-29W3	A 6	IV T1	561.0 - 565.0			Abandoned
Northrock 102 Medhat 10-27-18-1W4	B 1	IV III-IV V VI T1 II	1349.1 - 1350.1 1362.9 - 1363.8 1382.9 - 1383.9 1437.0 - 1438.0 1452.1 - 1453.1 1481.0 - 1482.0 1349.1 - 1482.0	11.69 (F)	No Data	Producing
NCO Horsham MT 11-8-18-29W3	B 2		1250.0 - 1685.0		No Data	Standing Production from Medicine Hat
BVI Hatton 6-22-17-28W3	B 3	III-IV VI T1	436.0 - 437.0 438.5 - 440.5 455.0 - 458.0	8.07 (C)	No Data	Combined Milk River and Medicine Hat

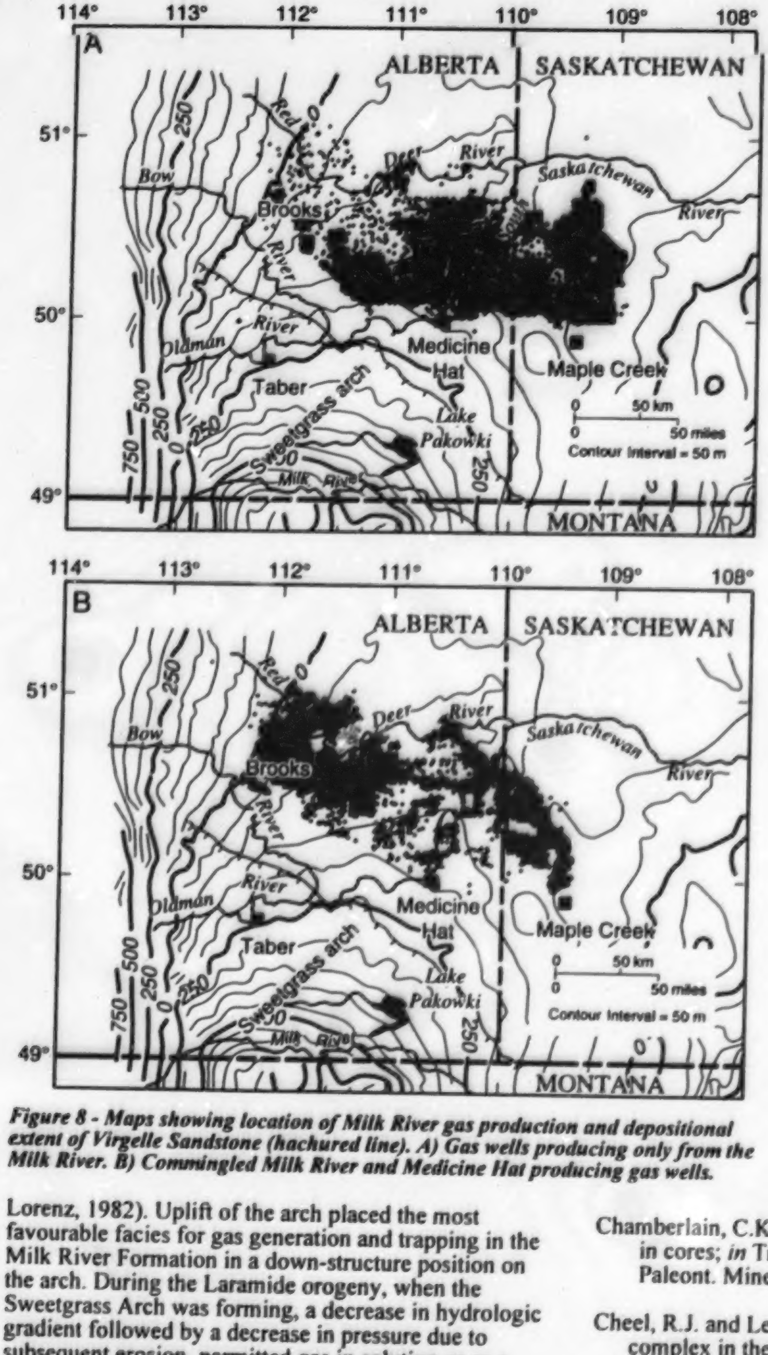

Figure 8 - Maps showing location of Milk River gas production and depositional extent of Virgelle Sandstone (hachured line). A) Gas wells producing only from the Milk River. B) Commingled Milk River and Medicine Hat producing gas wells.

Lorenz, 1982). Uplift of the arch placed the most favourable facies for gas generation and trapping in the Milk River Formation in a down-structure position on the arch. During the Laramide orogeny, when the Sweetgrass Arch was forming, a decrease in hydrologic gradient followed by a decrease in pressure due to subsequent erosion, permitted gas in solution or as a free phase to migrate. The gas was trapped in downdip parts of the arch where pinch out or truncation of facies occurs. Individual accumulations may have been locally sourced and eventually coalesced to form larger accumulations and permeability barriers to downdip water migration. During this process, gas exsolved and filled available pore space. Growth of the gas accumulation occurred in the upstructure direction through permeable facies or laterally as waters were diverted around permeability barriers. The extent of the gas accumulation upstructure or laterally and the duration of gas migration and exsolution are not known.

9. Future Studies

Future studies will further refine the depositional model for the Milk River within a sequence stratigraphic context. These data will be incorporated with studies of the Eagle Sandstone in Montana (Rice and Shurr, 1983) and will form the geologic framework for future gas assessments of shallow biogenic gas in the Northern Great Plains.

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B. Appendices

Saskatchewan–North Dakota Memorandum of Understanding on Exchange of Geological Information and Services

1. Preamble

Whereas it is in the best interest of North Dakota and Saskatchewan to make information and data readily available to operators in North Dakota and Saskatchewan in order to foster effective and responsible development of the mineral resources of the respective jurisdictions;

And whereas the importance of the mineral resource industry to the economies of North Dakota and Saskatchewan is recognized;

Now therefore, Saskatchewan and North Dakota agree as follows:

2. Definitions

"Saskatchewan" means her Majesty the Queen in Right of the Province of Saskatchewan as represented by the Executive Director of Exploration and Geological Services, Saskatchewan Department of Energy and Mines or any person authorized to act on his behalf.

"North Dakota" means the State of North Dakota as defined by the constitutions and laws of the United States and North Dakota.

"Parties" means Saskatchewan and North Dakota, and "Party" means either North Dakota or Saskatchewan.

"Coordination Committee" is the committee established pursuant to this MOU to guide coordination of geological survey cooperative activities.

3. Purpose of Agreement

To provide the Parties with a practical and effective instrument to pursue a cooperative and coordinated approach to mineral development issues of mutual interest.

4. Objectives

Cooperate in encouraging the economic development of the mineral resources of North Dakota and Saskatchewan.

Provide ready access to operators in North Dakota and Saskatchewan to public information that will stimulate development.

Cooperate in the preparation of geological studies, or other forms of information, of mutual interest to both Parties.

Foster improved cooperation and coordination of the activities of the mineral development staffs of the Parties.

Share information and research on the mineral resources of mutual interest to both Parties.

5. Responsibilities and Activities

Within the objectives of this MOU, the Parties undertake to assess and implement areas of cooperation and coordination as outlined in the objectives above.

Specifically, the Parties will each appoint two individuals to a coordination committee pursuant to Section 6 below. The Parties will also be responsible for developing proposals for assessment by the Coordination Committee as being within areas of mutual interest to both Parties and being acceptable within the terms of this MOU.

The Parties will be responsible for making their public databases and other public sources of geological information available at no cost to employees of the other Party at the discretion of the Coordination Committee.

The Parties will be responsible for encouraging increased interaction and cooperation of their employees with employees of the other Party to pursue the Objectives and Purpose of this MOU.

The Parties will each be responsible for evaluating their ongoing participation in this MOU.

6. Process

Individual projects or activities undertaken subject to the Objectives and Purpose of this MOU will be approved through the Coordinating Committee.

The Coordinating Committee will meet at least once a year to discuss issues related to this MOU, report on progress, establish priorities and approve projects for implementation under this MOU. The meeting will occur at a location of mutual convenience, but should alternate between jurisdictions. Other meetings of the Coordinating Committee should take place as necessary, but could be accomplished through the use of electronic media.

The Coordinating Committee may also choose to assign on a project basis one Party or the other as lead agent for purposes of administrative or technical convenience. Notwithstanding the assignation of one Party as lead agent, each Party will retain administrative control of the resources assigned to a particular joint initiative.

Any project or initiative designed to further the development of mineral resources in the jurisdictions of the two Parties and of mutual interest to both Parties will be eligible for implementation under the guidance of the Coordinating Committee. Such projects or initiatives could include, but should not be limited to:

i) Free access to public information and other public material of mutual interest to both Parties;

ii) Joint publication of studies and research of mutual interest to both Parties;

iii) Cooperation in undertaking cross-border geological studies and preparation of regional cross-sections;

iv) Display of relevant publications by both Parties; and

v) Joint initiatives to promote economic activity within the mineral resource sector in both jurisdictions.

Any publicity or public information related to joint activities undertaken through this MOU should provide equal recognition for both Parties. The Coordinating Committee will determine what information is to be made available to the public.

7. Duration of Agreement

This MOU shall be in force for a period of two (2) years from the date of the second signature of ratification. Extension of this MOU for additional periods of two years shall be by mutual consent of both Parties.

8. Amending Process

Amendment to this MOU shall be made by mutual consent of both Parties signatory to this MOU. Any amendment shall take the form of an exchange of letters.

Termination of this MOU shall be accomplished by either Party providing the other with six (6) months' written notice of its intent to terminate participation in this MOU.

Signed by:

Executive Director,
Exploration and Geological Services Division,
Saskatchewan Energy and Mines

State Geologist and Director of the North Dakota
Geological Survey, a Division of the Industrial
Commission for the State of North Dakota

The first Memorandum of Understanding between Saskatchewan and North Dakota was signed in April 1994. It covered a two-year period and heralded cross-border exchange of geological information important to both these jurisdictions and to oil companies working in the Williston Basin. A major resulting initiative was, and remains, the Annual International Horizontal Well Workshop. A more recent area of co-operative development is the use of CO_2 from North Dakota for PanCanadian's Miscible CO_2 Flood to revitalize oil recovery from its Weyburn pool. It is in the spirit of continuing the exchange of geoscience data and of various resources for the benefit of the people of Saskatchewan and North Dakota that this current Memorandum has been drawn up for signing in Bismarck at the Eighth International Horizontal Well Workshop.

Titles and Abstracts of Recent Saskatchewan Energy and Mines Publications and Papers by Staff of the Saskatchewan Geological Survey

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1. Miscellaneous Reports

Bennett, R.W. (1998): Assessment Work Catalogue, Saskatchewan; Sask. Energy Mines, Misc. Rep. 98-6, Part 1, p1-650.

Bennett, R.W. (1998): Assessment Work Catalogue, Saskatchewan; Sask. Energy Mines, Misc. Rep. 98-6, Part 2, p651-1302.

2. Maps

Macdonald, R. and Slimmon, W.L. (compilers) (1999): Geological Map of Saskatchewan; Sask. Energy Mines, 1:1 000 000 scale.

Saskatchewan Energy and Mines (1999): Mineral Resource Map of Saskatchewan; Sask. Energy Mines, 1:1 250 000 scale.

3. Digital Products

Slimmon, W.L. (1998): Geological Map of Saskatchewan; Sask. Energy Mines, CD-ROM, version 1.

Slimmon, W.L. (1999): Geological Atlas of Saskatchewan; Sask. Energy Mines, CD-ROM, version 2.

Watters, B.R. (1999): Compilation of lithogeochemical data from the northern Saskatchewan Shield; Sask. Energy Mines, Data File 19, 36p and one CD.

4. External Papers

(Saskatchewan Energy and Mines staff are indicated by **bold** type face)

Ansdell, K.M., Corrigan, K., Stern, R., and ***Maxeiner, R.O.*** *(1999): Shrimp U-Pb geochronology of complex zircons from Reindeer Lake, Saskatchewan: Implications for timing of sedimentation and metamorphism in the northwestern Trans-Hudson Orogen: GAC-MAC Joint Annual Meeting, Sudbury 1999, Abst. Vol., p3-4.*

Amphibolite-grade sedimentary and magmatic rocks of the northwestern margin of the Trans-Hudson Orogen are exposed on Reindeer Lake, Saskatchewan, within north-dipping structural panels. As part of the multidisciplinary La Ronge–Lynn Lake Bridge Project, zircons were obtained from five clastic metasedimentary rocks, chosen to constrain the age and provenance of sediments now preserved at different structural levels. These were analysed by the GSC SHRIMP II ion microprobe.

Detrital zircons have overgrowths, and complex cores, which include fragments of igneous zircons with lobate recrystallization textures. The northernmost sample, the Milton Island turbidites (MT), yielded core ages ranging from 1864 ±11 to 2829 ±8 Ma. This indicated a significant older component to the source, potentially the Hearn craton, but also constrains sedimentation to between 1864 and 1859 +3/-2 Ma, the age of the crosscutting Butler Island diorite. The north-dipping Duck Lake shear zone (DLSZ), separates MT from the structurally-underlying McLennan Group (ML), and Levesque Bay assemblage (LB). Probability distribution plots emphasize that ML basal conglomerate and overlying psammite contain a major population of 1845 to 1850 Ma zircons, whereas deeper water metapelites to the south are dominated by 1855 to 1860 Ma zircons. The LB, which pre-dates the 1867 ±4 Ma tonalite, are imbricated with these rocks within the Levesque Bay thrust zone. The ages also suggest that the ML and equivalents, the LB sediments were likely derived from the La Ronge/Wathaman continental arc system. In contrast to the MT, older >1.9 Ga zircons are rare to the south of the DLSZ.

Metamorphic overgrowths and grains are especially common in the more pelitic MT and LB samples, and exhibit uniform cathodoluminescence characteristics, low Th/U (~0.02), and high U concentrations (~1000 ppm). Zircon growth occurred between 1818 and 1805 Ma in the LB, but as late as 1789 Ma in the MT. The former ages are characteristic of peak regional metamorphism throughout most of the Trans-Hudson Orogen, although the significance of the younger age is presently unclear. The contrast in type and age of sedimentation, and difference in timing of metamorphic zircon growth does suggest that the DLSZ represents a major tectonic break.

Ashton, K.E.*, Froese, E., and Legault, A. (1999): Recognition of felsic volcanic rocks and hydrothermal alteration in moderately to highly metamorphosed parts of the Flin Flon volcanic belt;* ***in*** *Ashton, K.E. and Harper, C.T. (eds.), MinExpo '96 Symposium – Advances in Saskatchewan Geology and Mineral Exploration, Sask. Geol. Soc., Spec. Publ. No. 14, p27-43.*

In the amphibolite facies terrains north of Flin Flon, the Flin Flon volcanic belt is represented both as continuous extensions (e.g. the Wildnest-Mirond and Kisseynew lakes areas) and more isolated occurrences (e.g. Sherridon and Scimitar Lake areas). In the absence of primary features, it has generally been assumed that the felsic gneisses in these terrains were derived from plutonic or sedimentary precursors. However, the composition of many of these felsic gneisses could also indicate volcanic protoliths, and the spatial association of intermediate to mafic gneisses, amphibolite, VMS-type sulphide mineralization (e.g. Sherridon, FON, Teejay, and DRS deposits), and metamorphosed hydrothermal alteration supports a volcanic origin.

Four alteration types are recognized: calcic (clinopyroxene, epidote, calcite), ferromagnesian (cordierite, garnet, orthoamphibole, cummingtonite), potassic (muscovite, biotite), and aluminous (aluminum silicates). Several of these commonly occur together (e.g. at Sherridon and Wildnest Lake), which allows easy recognition of potentially mineralized areas. The association of altered rocks with felsic gneisses and amphibolites is particularly interesting and should act as an incentive for more detailed exploration of these high-grade terrains.

***Ashton, K.E. and Harper, C.T.** (editors) (1999): MinExpo'96 Symposium – Advances in Saskatchewan Geology and Mineral Exploration, Sask. Geol. Soc., Spec. Publ. No. 14, 163p.*

***Ashton, K.E.**, Heaman, L.M., Lewry, J.F., Hartlaub, R.P., and Shi, R. (1999): Age and origin of the Jan Lake Complex: A glimpse at the buried Archean craton of the Trans-Hudson Orogen; Can. J. Earth Sci., v36, p185-208.*

The largely buried Sask Craton is a continental fragment or microcontinent that collided with and underthrust the Paleoproterozoic Flin Flon–Glennie protocontinent along the Pelican Décollement Zone at 1840-1830 Ma. Rocks of the Sask Craton are exposed in three tectonic windows. Those of the Pelican Window have been named the Jan Lake Complex and comprise ≥2960 Ma arc-derived leucocratic orthogneisses, migmatitic paragneisses, and a tholeiitic, within-plate igneous suite comprising 2488 Ma dioritic to gabbroic rocks and 2450 Ma enderbitic and charnockitic rocks including the Sahli Granite. Ages of ca. 2450 Ma are also common from the other two tectonic windows to the Sask Craton, suggesting that emplacement of the igneous suite was widespread and perhaps part of the coeval Matachewan Igneous Event. The absence of rocks in the ≥2960 and ca. 2450 Ma age ranges on both the adjacent Superior and Rae-Hearne cratonic margins makes it improbable that the Sask Craton was derived by simple fragmentation without large-scale tectonic transport. The overthrust Paleoproterozoic rocks represent a high-grade northwestern extension of the Flin Flon volcanic belt and include 1856 Ma leucotonalite and 1843 Ma quartz monzodiorite. An 1830 Ma suite of homogeneous, calc-alkaline enderbitic rocks, which intrude Burntwood semipelitic migmatites throughout the Kisseynew Domain, has also been emplaced in mylonites of the Pelican Décollement Zone. Zircon and monazite ages in the 1812-1803 Ma range record a high-grade metamorphic event that resulted from collision between the Sask Craton and Flin Flon–Glennie Complex.

*Christopher, J.E., **Gilboy, C.F., Paterson, D.F.**, and Bend, S.L. (eds.) (1998): Eighth International Williston Basin Symposium, Sask. Geol. Soc., Spec. Publ. No. 13, 290p.*

*Corrigan, D., Lucas, S.B., Thériault, R., **Maxeiner, R.O.**, and Ansdell, K.M. (1999): Terrane assembly and tectonomagmatic evolution of the northwestern Reindeer Zone, Trans-Hudson Orogen: Insights from the Reindeer Lake Transect; GAC-MAC Joint Annual Meeting, Sudbury 1999, Abst. Vol., p26.*

The northwestern Reindeer Zone along Reindeer Lake, Saskatchewan, forms a north-northwest dipping imbricate stack that consists of juvenile volcanic arc rocks, sedimentary basins of various ages and tectonic setting, plutonic rocks including the ca. 1.86 Ga Wathaman Batholith, and the Archean Peter Lake Domain. The structurally lowest level (Kisseynew Domain) consists of <1.84 Ga fluvial sediments (McLennan/Sickle Group) that appear to grade southwards into Burntwood Group turbidites, suggesting the deepening of a sedimentary basin in that direction. Geological relationships in the McLennan/Burntwood transition zone are obscured by high-strain zones and the occurrence of narrow thrust slices comprising supracrustal rocks older than ca. 1.87 Ga and tentatively correlated with the La Ronge arc.

The Kisseynew Domain is overthrust along its northern flank by the La Ronge Domain, which consists of ca. 1.88-1.89 Ga volcanic and associated sedimentary rocks (Central Metavolcanic Belt) intruded by 1.86-1.85 Ga calc-alkaline plutons. Turbiditic sediments (Milton Island assemblage) structurally and stratigraphically overly the volcanic rocks and are interpreted as remnants of another basin, flanking the Central Metavolcanic Belt.

North of the La Ronge Domain, higher-grade equivalents of the Central Metavolcanic Belt, Milton Island assemblage, and a ca. 1.89 Ga orthogneiss complex of dioritic to granitic composition yielding a juvenile ε-Nd signature can be traced to the south margin of the Wathaman Batholith, where they are intruded by the latter. This assemblage corresponds to the Rottenstone Domain, which appears to represent the higher-grade equivalent of the La Ronge Domain in the study area.

A recently identified assemblage of clastic metasedimentary rocks (Park Island assemblage) occurring immediately south of the Wathaman Batholith consists of polymictic conglomerate grading stratigraphically upwards into arkosic sandstone, calcareous sandstone and siltstone. Structural relationships suggest that the Park Island assemblage was deposited on previously folded rocks of the La Ronge Domain and subsequently intruded by the Wathaman Batholith. We speculate that the Park Island assemblage was deposited in the forearc basin between the Hearne margin and the advancing La Ronge arc shortly before the emplacement of the Wathaman Batholith. The present day crustal architecture can be inferred to be the result of continued post-collisional convergence.

***Delaney, G.D.** (1999): Gold in the Glennie Domain: Relationship to a major temporal break in the supracrustal succession; **in** Ashton, K.E. and Harper, C.T. (eds.), MinExpo'96 Symposium – Advances in Saskatchewan Geology and Mineral Exploration, Sask. Geol. Soc., Spec. Publ. No. 14, p71.*

The Glennie Domain of the Trans-Hudson Orogen, northern Saskatchewan, contains in excess of eighty gold occurrences and one gold producer, the Seabee mine at Laonil Lake. Nearly all occurrences are within or adjacent to greenstone belts; by far the greatest number of showings, including the Seabee orebodies, are hosted in the Pine Lake Greenstone Belt. Gold-quartz veins occur in shear zones in a variety of rock types including volcanics, volcaniclastics, sediments, intrusions (both subvolcanic and younger post-volcanic suites), and migmatites. They are also in close spatial association with a major stratigraphic break that separates two distinct assemblages of supracrustal rocks and two major suites of intrusions. The older supracrustal assemblage, which is commonly more volumetrically extensive, consists of ca. 1890 Ma mafic to intermediate volcanic, volcaniclastic, and subvolcanic intrusive rocks emplaced in anomalous island arc settings. The older suite of intrusions comprises granodioritic and tonalitic plutons emplaced between 1846 and 1859 Ma. The younger supracrustal assemblage is a ca. 1840 Ma succession of volcaniclastic, sedimentary, and minor intermediate to felsic volcanic rocks, which at least locally are overlain by a thick sequence of arkose, grit, and conglomerate. A second, volumetrically more restricted suite of granodioritic to granitic intrusions were emplaced between 1828 and 1836 Ma.

Gold mineralization occurs in secondary or tertiary shear zones typically developed in areas of lithologic heterogeneity during D2 regional deformation. Gold is associated with quartz veins, alteration phases, and sulphide minerals and is paragenetically late. D3 and/or D4 deformation events and syn- to post-D3 amphibolite facies metamorphism are superimposed.

Dunn, C.E., ***Haidl, F.M.****, Yeager, J.R., Butrenchuk, E., Dorval, D., and Larson, B. (1998): Surface geochemical patterns derived from selective leaching of soils over a deep Ordovician oil pool, Bromhead, southeastern Saskatchewan;* ***in*** *Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L. (eds.), Eighth International Williston Basin Symposium, Sask. Geol. Soc., Spec. Publ. No. 13, p254-265.*

Surface geochemical detection of deeply seated hydrocarbons is an inexact science. It has been firmly established that there is upward movement of chemical compounds from hydrocarbon reservoirs. Therefore the challenge is to develop economical methods to assist in differentiating those seismic anomalies that represent barren structures from those that host hydrocarbons.

The recently developed enzyme leach method of extracting elements loosely bound to amorphous manganese oxide coatings on soil particles has been tested in southeastern Saskatchewan. The target, an Ordovician Red River reservoir at a depth of 2850 m, was studied by collecting soil samples from 74 sites within a one square mile (2.6 km^2) section. A 3-D seismic structure that is quite pronounced at the Ordovician Winnipeg–Red River formation level is outlined by a number of element enrichments in the soils that flank its surface projection. Of note are relative enrichments of the halogens (Br, I, Cl) and of Mo, Re, W, V, As and Sb. Copper, Ni, Ba, Cd, Sr and U also show positive but less distinctive relationships to the structure.

Fanton, K., Holmden, C., Nowlan, G., and ***Haidl, F.M.*** *(1998): Nd and C isotope stratigraphy of Ordovician carbonates in the Williston Basin,* ***in*** *Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L. (eds.), Eighth International Williston Basin Symposium, Sask. Geol. Soc., Spec. Publ. No. 13, p8.*

Nd and C isotopic profiles were constructed for a section of Ordovician cores from southeastern Saskatchewan in order to investigate Nd and C isotopic distributions within the Williston Basin. The Yeoman and Herald formations show large (3‰) variations in $\delta^{13}C$ values which mirror changes in lithology. In contrast, C isotopic values are more uniform within the Hartaven, Gunn and first 10 m of the Gunton members of the Stony Mountain Formation. This correspondence between $\delta^{13}C$ values and lithology reflects carbon cycling within the Williston Basin and therefore suggests a method for correlating carbonate sequences, provided that factors operative in southeastern Saskatchewan are representative of the whole basin.

Minute amounts of Nd dissolved in seawater are derived from river inputs and the isotopic composition reflects the average age of the surrounding crust. Previous studies have shown that a substantial shift in the isotopic composition of Nd in Lower Paleozoic clastics indicates that a major change in the age of emergent continental crust had occurred throughout North America. We have found this Nd isotopic shift within the Yeoman Formation of the Williston Basin. Pre-shift epsilon values are -17, whereas post-shift epsilon values range between -7 and -9 for the rest of the sampled section. The magnitude and singularity of this shift within the Ordovician provide another means of correlating strata within the Williston Basin. The pre-shift values are a result of river inputs from Precambrian rocks, including those exposed on the Transcontinental Arch. Less negative post-shift values indicate a source terrain substantially younger in crustal age. The similarity in εNd values (-7 to -9) within the Williston Basin to εNd values (-6 to -9) of Appalachian clastics suggests an emergence of a common Taconic watershed and submergence of the intervening Transcontinental Arch during deposition of the Yeoman. The persistence of the less negative εNd values (-7 to -9) throughout the rest of the section may be interpreted to reflect continued submergence of the arch.

Grieve, R.A.F., ***Kreis, L.K.****, and Therriault, A.M. (1998): Impact structures of the Western Sedimentary Basin of North America: New discoveries and hydrocarbon resources;* ***in*** *Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L. (eds.), Eighth International Williston Basin Symposium, Sask. Geol. Soc., Spec. Publ. No. 13, p189-201.*

Seven impact structures are now known from the Western Sedimentary Basin of North America. This contribution reports on the discovery of shock metamorphic effects at three of these structures: Elbow, Maple Creek and Viewfield, all in Saskatchewan. It also describes their general character and that of the other impact structures in the basin. Particular emphasis is placed on the production of hydrocarbons from these structures, which ranges from none to 1000 BOPD (at Red Wing Creek, North Dakota). Other hydrocarbon-producing impact structures in Canada, Mexico and the United States are briefly characterized along with their productivity. Most production at impact structures occurs from structural traps in the rim and central uplift and from brecciated target rocks, including crystalline rocks. The most productive impact-related hydrocarbon reservoir rocks are breccias in the Gulf of Mexico believed to be genetically linked to the K/T impact that formed the Chicxulub structure on the Yucatan Peninsula, Mexico. Many impact structures remain to be discovered throughout the world. For example, the current estimate of the terrestrial cratering rate indicates that as many as 12 ±6 impact structures with diameters of 10 km or greater remain to be discovered in the Williston Basin. If half of them have reserves similar to the 9 km diameter Red Wing Creek structure, the cumulative potential impact-related reserves are in the order of 1 BBO and 600 BCFG in the Williston Basin alone.

Harper, C.T. *(1999): Structural styles in, and transitions from, the La Ronge, Kisseynew and Glennie Domains, Waddy Lake–Southend Region;* ***in*** *Eighth LITHOPROBE Trans-Hudson Orogen Transect Workshop, Saskatoon, Feb. 25-26, 1999.*

Recent geological mapping of the northeastern extension of the La Ronge Domain, including parts of the MacLean Lake Belt (Kisseynew Domain) and northern extremity of the Glennie Domain in the region between Waddy Lake and Southend (Harper, 1996, 1997, 1998; Maxeiner, 1996), has revealed some interesting structural features and contrasts. Each of the three domains has a different lithological character and structural style. The structural transitions between the domains can be correlated to the LITHOPROBE seismic reflection Line S2B, which transects part of this area.

The Central Metavolcanic Belt (CMB) of the La Ronge Domain in the Waddy Lake area comprises ultramafic to felsic volcanic and plutonic rocks with minor volcaniclastics (Harper, 1984, 1985). The CMB essentially acted as a rigid structural domain preserving less deformed and lower metamorphic grade rocks. It is typified by steep to subvertical dips, regional homoclinal to isoclinal folds, and pressure-shadow style deformation around the 1855-1850 Ma plutons and tighter deformation aureoles around the younger 1835 Ma plutons. Small-scale folds are rare in the CMB. The boundary with the adjacent sedimentary belts is marked in part by an unconformity, locally represented by a basal polymictic conglomerate, but also by a high-strain zone, which places the CMB structurally above the younger metasediments of the MacLean Lake Belt (MLB).

The MacLean Lake Belt (MLB), which is more appropriately considered part of the Kisseynew Domain, mainly comprises psammitic to pelitic gneisses, with lesser amphibolitic (mafic volcanics) and calc-silicate gneisses. Feldspathic psammites and minor conglomerate of the McLennan Group represent the youngest near shore sediments of the sequence. Intrusive sheets of ultramafic to felsic composition are a minor component. Deformation and metamorphism increase in intensity and grade (attaining granulite grade) away from the CMB. The MLB is characterized by decreasing dips away from the contact with the CMB, becoming very shallow to subhorizontal SE of the Stanley Shear Zone (SSZ). The SSZ also marks a change in structural style. To the NW are strongly linear, highly attenuated structures disrupted by numerous parallel thrust faults producing a complicated structural interleaving of metasediments and metavolcanics. A well-developed stretching lineation plunges shallowly NNE. This imbricate thrust zone extends northeast to and across Reindeer Lake (Maxeiner, 1997, 1998; Corrigan *et al.*, 1997, 1998). Southeast of the SSZ are large-scale, open dome and basin and mushroom-shaped interference structures, which refold an earlier formed porphyroclastic texture. As a result of the folding, the equivalent stretching lineation is highly variable in attitude. The transition to the Glennie Domain, along the NW margin and along the east margin near Southend, is marked by a prominent mylonite zone affecting rocks of both domains. The early-formed porphyroclastic-textured mylonite is folded and refolded. Pseudotachylite veins and blebs occur in the mylonite locally. Delta wing porphyroclasts and shear folds show a consistent sinistral shear sense consistent with the Kisseynew Domain (and La Ronge Domain) being thrust southwestwards.

The northern margin of the Glennie Domain comprises highly strained, upper amphibolite to granulite grade, mafic to felsic plutonic rocks, termed the Gloeckler Lake Intrusive Suite (Harper, 1998), and predominantly pelitic metasediments with minor amphibolitic and calc-silicate gneisses interpreted as thrust nappes of Kisseynew gneisses on the Glennie Domain. This part of the Glennie Domain has shallow to moderate dips with a well-developed stretching lineation of variable attitude because of refolding as in the MLB. The mylonitized margin gives way to larger, open interference structures involving the Kisseynew nappes. The Glennie Domain also acted as a more rigid block, with the more plastic Kisseynew metasediments squeezed between it and the La Ronge Domain.

Previous structural interpretations of the seismic reflection line S2B, that followed highway 905 north from the junction with highway 102, show several features which need to be addressed. Hajnal *et al.* (1996) shows a narrow strip of Glennie Domain at the southern end of the transect. This is in fact part of the MLB (Kisseynew Domain) with the nearest part of the Glennie Domain being exposed at Street Lake (Harper, 1998) about 4.5 km to the SE. At an average dip of 30 degrees, the Glennie-Kisseynew domain boundary would intersect the plane of the transect at a depth of about 2.5 km, below the prominent reflector indicated on the section. The wedge shaped area beneath the southern end of line S2B could be all Glennie Domain or could include part of the Sask Craton.

In the LITHOPROBE Phase V Proposal volume (Clowes, 1997), the interpretive drawing of Line S2B shows a much narrower La Ronge Domain compared to the Rottenstone Domain which doesn't agree with the geology of the transect. The second point is that the entire wedge-shaped area beneath the southern end of Line S2B is depicted as being Sask Craton. This would mean that a very thin slice of the profile would be representative of the Kisseynew Domain. Also if that interpretation were correct, the Sask Craton would project to surface at the same position as the Kisseynew-Glennie boundary at Street Lake, or could be at a shallow depth beneath a thin skin of Glennie Domain granitoid rocks. Certainly dating rocks of the Gloeckler Lake Intrusive Suite would provide some valuable information on the northern margin of the Glennie Domain.

At this time there are still a number of unanswered questions regarding the northern part of the Reindeer Zone.

1. Although we know that volcanism, plutonism and sedimentation among the La Ronge, Glennie and Flin Flon arcs were contemporaneous, we are still uncertain whether they were linked in any way. Perhaps they were related in a similar fashion as the southwest and western Pacific.

2. What was the role of the Sask Craton? Was it an indentor, driving beneath the Flin Flon–Glennie arc terrain or was it also a transporter, carrying the over riding Glennie and Kisseynew thrust plates northward to collide and be overthrust by the La Ronge Domain?

3. How far north does the Sask Craton extend and is it imaged in the seismic reflection Line S2B? If one of the structural interpretations of Line S2B is correct, is the Sask Craton exposed in the northern Glennie Domain? Isotopic studies on pegmatites from this region and further geochronological studies could provide the answers.

4. If the Kisseynew basin represents some combination of back-arc or interarc basin, was there any oceanic crust developed and if there was where is it? It could have been entirely subducted. Geological mapping and geochemical studies of the amphibolite gneisses of the MLB (Harper, 1996, 1997, 1998; Hasanie and Harper, 1997; Hasanie, 1998; Harper and Hasanie, this meeting) have shown that they are primarily derived from pillowed metabasalts. The amphibolites have a consistent ocean floor basalt (or N-MORB) chemical affinity with some transitional affinity to volcanic arc basalts which is characteristic of back arc basalts.

Therefore, these rocks are the best candidates for the missing oceanic crust.

Harper, C.T. and Hasanie, R. (1999): Geochemistry and tectonic implications of amphibolite gneisses of the MacLean Lake Belt, Waddy Lake–Southend region; in Eighth LITHOPROBE Trans-Hudson Orogen Transect Workshop, Saskatoon, Feb. 25-26, 1999.

Amphibolites of the MacLean Lake belt (MLB) have been variously interpreted to be derived from sedimentary, volcanic, and plutonic protoliths. This diversity of opinion in part reflects the high-metamorphic grade, the lack of preserved primary structures, and misinterpretation of the effects of early carbonate alteration of the amphibolites. During recent remapping of the region between Waddy Lake and Southend (Harper, 1996, 1997, 1998), the nature and origin of these rocks were investigated through field examination, petrography, and whole rock and trace element geochemistry (Hasanie and Harper, 1997), which formed the basis of an honours thesis by Hasanie (1998). The earlier results are augmented by additional geochemical data obtained during the 1998 mapping season.

The amphibolites commonly cap prominent topographic ridges and are generally better exposed than other rock types of the MLB. They are interlayered with metasediments of the MLB (part of the Kisseynew Domain) and are very commonly associated with a calc-silicate assemblage (marble, quartzite/metachert, calcareous psammopelite) of sedimentary derivation. The amphibolites also have a calcareous component consisting of pods, lenses, and bands comprising variable amounts of epidote, diopside, carbonate, plagioclase, quartz, garnet, sphene, and sulphides. This component, which is interpreted as representing early alteration of mafic volcanics, commonly produces a streaky to banded habit, which undoubtedly caused some workers to think of them as metasediments.

Johnston (1969, 1970, 1982, 1983), who mapped this region at 1:63,360 scale in the mid 60's to early 70's, had recognized pillow structures in a few places and generally considered the amphibolites to be metabasalts. Harper (1996, 1997, 1998) also considers the amphibolites to be primarily of volcanic origin based on recognition of pillow structures, together with fragmental textures, intercalation of minor intermediate to felsic varieties, and the early volcanogenic calcareous and siliceous alteration.

The amphibolites comprise massive and well banded varieties. The massive type tends to be a black to dark greenish black, coarser gained hornblende-plagioclase rock that in places has a rectilinear net-veined character. Locally this type may have a spotted appearance caused by abundant plagioclase porphyroblasts, some of which have a core of garnet. The massive types may represent thicker flows or intrusive sills. The banded type has alternating dark green to black hornblende-rich layers and pale to medium green diopside-bearing layers. Calcite is locally abundant and weathers recessively. In most outcrops of this type flattened ovoid shapes, V-shaped intersections, and amphibole±biotite±garnet-rich 'selvages' suggest that these rocks originated from altered pillowed flows.

Rock samples used for geochemical studies were selected on the basis of the least evidence of alteration and compositional homogeneity. Samples collected in 1996 were analyzed by Bondar Clegg, Vancouver, in 1997 by Acme Analytical Laboratories Ltd., Vancouver, and in 1998 by Activation Laboratories Ltd., Ancaster. Except for the rare earth elements (REE) the analyses from the three companies were very consistent. For comparative purposes metabasalts from the southeastern margin of the Central Metavolcanic Belt (CMB) of the La Ronge Domain are included.

The amphibolites have a narrow range of silica, from 48 to 51 percent, and show little evidence of alkali mobility on Harker type plots. On silica versus alkalis plots the amphibolites display subalkaline and low to medium potassium basaltic characteristics as do the CMB metabasalts. On the Jensen cation plot, the amphibolites mainly cluster in the high-iron tholeiite field compared to a broader spread for the CMB basalts, which cover high iron, high magnesium tholeiite and some calc-alkaline basalt fields. This probably reflects more diversity and/or alteration effects in the CMB rocks.

Immobile element basalt discrimination diagrams help resolve the tectonic setting in which the rocks were formed. The Ti/100-Zr-Yx3 ternary diagram (Pearce and Cann, 1973) shows the amphibolites and CMB basalts overlap the low potassium tholeiite (LKT) and ocean floor basalt (OFB) fields. On the Zr versus Ti diagram (Pearce and Cann, 1973) the generally higher Ti content of the amphibolites begins to show more of a distinction between them and the CMB basalts. The amphibolites plot near the upper limit of the LKT field as well as in the OFB and in the are where the two types overlap. Most of the CMB basalts plot near the lower end of the LKT field. On the Ti/100-Sr-Sr/2 ternary diagram (Pearce and Cann, 1973) the split is more evident, with the majority of the amphibolite samples plotting in the OFB field and a few falling in the island arc basalt (IAB) field. The CMB basalts mostly plot in the IAB field with several near or in the cal-alkaline basalt (CAB) field. The Cr versus Ti diagram (Pearce, 1975) shows a clear distinction with the amphibolites showing a relatively tight cluster and plotting entirely in the OFB field and the CMB basalt except for two samples plot within the LKT field. On the Nbx2-Zr/4-Y ternary diagram (Meschede, 1986) amphibolite samples from 1998 plot in the overlapping N-MORB and volcanic arc basalt field.

A primitive mantle normalized REE plot of the amphibolites shows a relatively flat profile which compares well with N-MORB and back-arc basalt (BAB) profiles of young basalts (Jenner, 1996). Similarly a MORB normalized spider plot for the amphibolites is most like the BAB profile (Jenner, 1996).

The chemical signatures of the amphibolites and CMB basalts generally indicate that they were derived from different magmatic sources and in different tectonic settings. The amphibolites typically show an OFB affinity with some transitional VAB character, whereas the CMB basalts generally show a VAB affinity. The locally preserved pillowed character of the amphibolites is also consistent with an OFB setting. The OFB and transitional VAB character together with the association with Kisseynew basin sediments is also consistent with the amphibolites having formed in a back arc tectonic setting. The interlayering of the amphibolites and sediments may be in part primary, but probably also due to thrust tectonics as the Kisseynew basin was destroyed between the colliding La Ronge and Glennie domains. The amphibolites potentially represent the missing oceanic crust of the Kisseynew basin.

Kelley, L.I. (1998): Industrial minerals of Saskatchewan: An overview of geology, production, and prospects; Focus on Industrial Minerals, Canadian Institute of Mining and

Metallurgy, Vancouver, October 1998, Abst., p65-67.

Industrial mineral production contributes on the order of CDN$1.5 billion per year to the economy of Saskatchewan. Potash is the primary industrial mineral produced in the province, followed by aggregate, sodium sulphate, salt, potassium sulphate, peat, clays, silica sand, calcium chloride brine, and "clinker". Potentially economic deposits of kaolin, diamond, and building stone are under evaluation.

Kelley, L.I. *(1999): Industrial minerals of Saskatchewan;* **in** *Johnson, K.J. (ed.), Proceedings of the 34th forum on the geology of industrial minerals, Norman, OK, Oklahoma Geological Survey, Circular 102, p309-312.*

Industrial-mineral production contributes on the order of CDN$1.5 billion per year to the economy of Saskatchewan, Canada. Potash is the primary industrial mineral produced in the province, followed by aggregate, sodium sulphate, salt, potassium sulphate, peat, clays, silica sand, calcium-chloride brine, and "clinker". Potentially economic deposits of kaolin, diamond, and building stone are under evaluation. All of the major deposits of commodities discussed here are located south of lat 56°30"N.

Kelley, L.I. *and Holmden, C. (1999a): Geochemistry of groundwater associated with economic deposits of sodium sulfate (mirabilite) in saline lakes of Saskatchewan, Canada; Seventh International Conference on Salt Lakes, Death Valley, California, Sept. 1999, Abst.*

Sodium sulfate has been mined from evaporite deposits in post-glacial, groundwater-fed, endorheic lake basins in Saskatchewan since 1918. Sodium sulfate is used in the manufacture of detergents, fresheners, glass, paper and textiles. Recently, Saskatchewan companies have pioneered the use of sodium sulfate in the value-added manufacture of potassium sulfate used as a fertilizer for chloride-sensitive crops.

We have begun a five-year project to advance understanding of the origin of these deposits as modern ore-forming systems. Because groundwater continues to supply ions to the lake basins through spring discharge, our approach is hydrogeological, with the major objective of quantifying fluid and chemical mass balances.

Our initial efforts are focused on evaluating which portion of the groundwater flow system supplies ions to the lake basins. Hydrogen and oxygen isotopes demonstrate that relatively shallow (<200 m) systems are the source of groundwater that discharges in springs near sodium sulfate deposits. Preliminary work with strontium isotopes shows that different inter-till aquifers appear to have different $^{87}Sr/^{86}Sr$ ratios. In some cases the lake brine isotopic composition matches that of groundwater discharging from springs. The challenge ahead is to determine whether strontium isotopes can be used to fingerprint specific aquifer inputs in a context of potential $^{87}Sr/^{86}Sr$ evolution along groundwater flow paths.

Kelley, L.I. *and Holmden, C. (1999b): Origin of sodium sulphate deposits of southern Saskatchewan, Canada: 1. Stable isotope and chemical composition of groundwater; 35th Forum on the Geology of Industrial Minerals, Salt Lake City, May 1999, Abst.*

Sodium sulphate is used in the manufacture of powdered detergents, carpet fresheners, plate (float glass), kraft paper and textiles. It is also reacted with potash to produce potassium sulphate. Sodium sulphate has been mined from lacustrine evaporite deposits in southern Saskatchewan since 1918. In 1997, three companies operated four sodium sulphate operations, and two other companies extracted sodium sulphate for potassium sulphate production. The total value of sodium sulphate and potassium sulphate produced in Saskatchewan in 1997 was approximately $CDN 40 million.

The deposits occupy post-glacial endorheic (closed) lake basins in a belt that stretches from northwestern North Dakota and northeastern Montana across southern Saskatchewan to east-central Alberta. Previous workers generally acknowledge the empirical relationship between evaporitic mineralization and the presence of active lake-bottom or peripheral springs. Groundwater discharging into the lake basins contains 1000 to 5000 ppm of total dissolved solids (TDS). Most of the TDS load is Na^+ and $SO_4^=$. Groundwater is viewed as a causative agent, but workers disagree on the ultimate origin of the groundwater (e.g. connate water, deeply circulating brines, or recent meteoric water) and the source of dissolved ions (e.g. Paleozoic evaporites deep in the sedimentary section, bentonite in Cretaceous mudstones, or till). None of the previous workers tested their hypotheses.

Hydrogen and oxygen isotope results for groundwater sampled from six sodium sulphate deposits suggest that the spring systems that currently supply ions to alkali lakes in southern Saskatchewan are not hydraulically connected to Paleozoic saline aquifers. Major ion chemistry suggests that the groundwater may be at least partly from a pre-Wisconsinan aquifer, perhaps mixed with shallow groundwater during ascent.

Lafrance, B., *Corrigan, D., and* **Sibbald, T.I.I.** *(1999): The Grease River Shear Zone: Proterozoic Reactivation along the margin of the Archean East Athabasca mylonite triangle in the Snowbird Tectonic Zone; GAC-MAC Joint Annual Meeting, Sudbury 1999, Abst. Vol., p65-66.*

The East Athabasca mylonite triangle (EAMT) is a deep-crustal mylonite zone at the boundary between the Rae and Hearne provinces. The EAMT is exposed over 75 km along the north shore of Lake Athabasca, Saskatchewan, but it disappears under the ca. 1.7 Ga Athabasca Basin, south of the lake. Deep-crustal shearing at ca. 2.6 Ga produced the regional, granulite-grade mylonitic foliation, which characterized the EAMT. The EAMT is bounded by narrow greenschist-grade shear zones, the Grease River Shear Zone (GRSZ), to the west and the Black Lake Fault to the east. The two shear zones have been previously interpreted as products of strain localization of the deep-crustal deformation into narrow strike-slip structures during Late Archean exhumation of the granulite terrain.

Mapping of the GRSZ along Lake Athabasca and geochronological constraints suggest that the GRSZ, is a Proterozoic shear zone, which overprints and reactivates the Archean structure with minor Proterozoic reworking, as previously inferred. The GRSZ forms the western margin of a wider, greenschist-grade, strain zone, which extends over 6 km in the EAMT. In this strain zone, the Archean mylonitic foliation is folded by open to tight folds with an axial planar cleavage, defined by flattened biotite and muscovite knots replacing garnet porphyroblasts. In the GRSZ, folding is more intense, and the folds, which plunge 40-50 degrees to the NE, consistently have dextral asymmetry. With increasing shear, the folds tighten, their axial planes rotate in clockwise fashion, and the folds become bounded by biotite-rich décollement zones parallel to the Archean mylonitic foliation. These structures and dextral shear bands are indicative of dextral transcurrent shear along the GRSZ. Muscovite- and biotite-bearing pegmatites and aplites cut across the Archean mylonitic foliation and are overprinted by the folds. Preliminary isotopic work produced a Proterozoic U-Pb zircon crystallization age for the dykes, suggesting a Proterozoic age for the GRSZ. A ca. 1.9 Ga, deformed, leucogranite dyke, 2.6 km northeast of the study area, cuts across the greenschist-grade foliation of the GRSZ, and further supports a Proterozoic age for the GRSZ.

Lucas, S.B., Syme, E.C., and ***Ashton, K.E.*** *(1999): New perspectives on the Flin Flon Belt, Trans-Hudson Orogen, Manitoba and Saskatchewan: An introduction to the special issue on the NATMAP Shield Margin Project, Part 1; Can. J. Earth Sci., v36, p135-140.*

A new tectonic framework for the Flin Flon Belt in southeastern Reindeer Zone of the Trans-Hudson Orogen has emerged in recent years through four-dimensional studies (bedrock and subsurface mapping, seismic reflection profiling, U-Pb geochronology) associated with the NATMAP Shield Margin Project and LITHOPROBE Trans-Hudson Orogen Transect. This special issue contains 10 papers covering a wide variety of topics related to the NATMAP Shield Margin Project.

Lucas, S.B., ***Ashton, K.E.****, Syme, E.C., Stern, R.A., White, D.J., Ansdell, K.M., and Ryan, J.J. (1999): Four-dimensional mapping of the Flin Flon Belt through interdisciplinary NATMAP and LITHOPROBE studies;* **in** *Ashton, K.E. and Harper, C.T. (eds.), MinExpo'96 Symposium – Advances in Saskatchewan Geology and Mineral Exploration, Sask. Geol. Soc., Spec. Publ. No. 14, p4-25.*

The southeastern Reindeer Zone is marked by a northeast-dipping, crustal-scale stack characterized by three principal elements which were juxtaposed during 1.84 to 1.80 Ga collisional deformation: 1) 3.20 to 2.40 Ga metaplutonic rocks and paragneisses of the 'Sask craton', exposed in the Pelican window; 2) 1.92 to 1.87 Ga juvenile arc and oceanic rocks, 1.88 to 1.84 Ga plutons, 1.87 to 1.85 Ga volcano-sedimentary packages (Schist-Wekusko assemblage), and 1.85 to 1.84 Ga alluvial-fluvial sandstones (Missi Group); and 3) 1.85 to 1.84 Ga marine turbidites (Burntwood Group) and distal facies of the Missi Group sandstones at the highest structural levels (Kisseynew Domain). The middle element in the stack comprises the Flin Flon Belt (now including the Attitti Block and Paleoproterozoic rocks in the Hanson Lake Block) and Glennie Domain (including the Scimitar Complex) and is here termed the Flin Flon–Glennie Complex (FFGC). The previous stratigraphic framework for Flin Flon Belt 'greenstones' (Amisk Group) is insufficient to account for the range in lithological and geochemical associations, Sm/Nd isotopic signatures, and U-Pb zircon ages. As a result, a series of 1.92 to 1.87 Ga arc and ocean floor assemblages have been distinguished. These assemblages are stitched together by cross-cutting plutons (1.88 to 1.84 Ga) and some are separated by early high-strain zones, suggesting that they were accreted to form a tectonic collage at 1.88 to 1.87 Ga. Post-accretion plutons and volcanic rocks (1.88 to 1.84 Ga) are attributed to younger successor arc(s) which were imposed on the collage contemporaneously with regional steepening of the early collision-accretion structures. Uplift and erosion, development of a paleosol and deposition of voluminous turbidites (Burntwood Group) and continental sedimentary rocks (Missi Group) occurred ca. 1.85 to 1.84 Ga, coeval with the waning stages of successor arc magmatism. Assembly of the crustal thrust stack occurred in response to collision of the Sask craton with the overriding FFGC. Due to structural interleaving, the boundary between the FFGC and Kisseynew Domain is best described as a structural-stratigraphic transition zone. In contrast, the boundary between the Sask craton and FFGC is a broad ductile shear zone termed the Pelican décollement zone. Initial thrusting was coeval with 1.84 to 1.83 Ga mafic-felsic calc-alkaline magmatism and ongoing continental sedimentation (Missi Group), and continued through peak regional metamorphism at 1.82 to 1.80 Ga. Oblique collision with the Superior craton occurred at about 1.81 Ga and led to post-collisional sinistral transpression of eastern Trans-Hudson Orogen (THO), with wrench faulting and refolding of the thrust stack producing considerable structural relief. The Namew Gneiss Complex, mapped beneath the Phanerozoic cover south of Flin Flon, represents the middle crust of the intraoceanic terrane juxtaposed against the exposed upper crustal levels by post-collisional wrench faulting.

Maxeiner, Ralf O. and Sibbald, Tom I.I. *(1999): Redefining contact relationships between McLennan Group and surrounding lithotectonic elements in the southern La Ronge Domain, Trans-Hudson Orogen, Saskatchewan:* **in** *Ashton, K.E. and Harper, C.T. (eds.), MinExpo'96 Symposium – Advances in Saskatchewan Geology and Mineral Exploration, Sask. Geol. Soc., Spec. Publ. No. 14, p55.*

The McLennan Group, a lithotectonic element of the La Ronge Domain, has traditionally been viewed as a molasse deposit lying unconformably upon rocks of the Central Metavolcanic Belt (CMB) and the MacLean Lake Belt (MLB). Structurally, it lies between these two northwest dipping belts, and is overthrust along much of its length by the CMB along the McLennan Lake Tectonic Zone. At the south end of the domain, the exposed relationship between the McLennan Group and the CMB is clearly interpreted to be an unconformity.

Based on recent remapping of parts of the region, two typically distinct supracrustal assemblages are recognized. Assemblage A (> ca. 1855 Ma), a predominantly volcano-plutonic assemblage that is exclusively made up of CMB rocks, comprises mafic to intermediate and minor felsic volcanics which are intruded by simple to multiphase plutons. Assemblage B (≤ 1855 Ma) is formed by polymictic volcanogenic conglomerate, psammite, calcareous psammite, psammopelite, trachytic-textured intermediate volcanics, amphibolite, and arkosic rocks including those of the McLennan Group. It is intruded by quartz-phyric granite porphyry, mafic to felsic dykes and sills, and multiphase granites. The basal parts of Assemblage B are characterized by a heterogeneous volcano-sedimentary succession that is gradational into and intercalated with overlying McLennan arkoses and arkosic conglomerates. Local unconformity exists between quartz-phyric granite porphyry, which intrudes polymictic volcanogenic conglomerate and overlying McLennan arkose, and arkosic conglomerate. However, major regional unconformity exists between Assemblage A and Assemblage B.

The basal, heterogeneous part of Assemblage B is of economic interest because it contains a diversity of gold occurrences which differ markedly from the shear zone-hosted deposits of the CMB. Examples of such occurrences are provided by showings at Greywacke Lake, Ramsland Lakes, and North Lake. The extended package of ca. 1840 to 1855 Ma supracrustals, overlying the CMB, and the similarly aged 'auriferous' volcano-sedimentary package now identified throughout the Glennie Domain, clearly represent a metallotect that has been underexploited because of a lack of deposit models.

Maxeiner, R.O., Sibbald, T.I.I., Slimmon, W.L., *Heaman, L.M., and Watters, B.R. (1999): Lithogeochemistry of volcano-plutonic assemblages of the southern Hanson Lake Block and southeastern Glennie Domain, Trans-Hudson Orogen: Evidence for a single island arc complex; Can. J. Earth Sci., v36, p209-225.*

This paper describes the geology, geochemistry, and age of two amphibolite facies volcano-plutonic assemblages in the southern Hanson Lake Block and southeastern Glennie Domain of the Paleoproterozoic Trans-Hudson Orogen of east-central Saskatchewan. The Hanson Lake assemblage comprises a mixed suite of subaqueous to subaerial dacitic to rhyolitic (ca. 1875 Ma) and intercalated minor mafic volcanic rocks, overlain by greywackes. Similarly with modern oceanic island arcs, the Hanson Lake assemblage shows evolution from primitive arc tholeiites to evolved calc-alkaline arc rocks. It is intruded by younger subvolcanic alkaline porphyries (ca. 1861 Ma), synvolcanic granitic plutons (ca. 1873 Ma), and the younger Hanson Lake Pluton (ca. 1844 Ma). Rocks of the Northern Lights assemblage are stratigraphically equivalent to the lower portion of the Hanson Lake assemblage and comprise tholeiitic arc pillowed mafic flows and felsic to intermediate volcaniclastic rocks and greywackes, which can be traced as far west as Wapawekka Lake in the south-central part of the Glennie Domain. The Hanson Lake volcanic belt, comprising the Northern Lights and Hanson Lake assemblages, shows strong lithological, geochemical, and geochronological similarities to lithotectonic assemblages of the Flin Flon Domain (Amisk Collage), suggesting that all of these areas may have been part of a more or less continuous island arc complex, extending from Snow Lake to Flin Flon, across the Sturgeon-weir shear zone into the Hanson Lake Block and across the Tabbernor fault zone into the Glennie Domain.

Norford, B.S., Nowlan, G.S., ***Haidl, F.M.****, and Bezys, R.K. (1998): The Ordovician-Silurian boundary interval in Saskatchewan and Manitoba;* ***in*** *Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L. (eds.), Eighth International Williston Basin Symposium, Sask. Geol. Soc., Spec. Publ. No. 13, p27-45.*

Biostratigraphic data based on macrofossils and conodonts from wells and outcrops in the Williston and Hudson Bay basins permit new interpretations of stratigraphic units within the Ordovician-Silurian boundary interval. On the basis of conodont data, the Ordovician-Silurian boundary has been restricted to an 8 cm interval that essentially coincides with the top of the upper t-marker in the Stonewall Formation in Saskatchewan and within a 2 m interval associated with the t-marker in other outcrops and wells in Manitoba. Correlations in the Hudson Bay region are less precise because of sparse data. A major disconformity is documented within the Stonewall Formation of the Williston Basin with the associated hiatus ranging from latest Ordovician (Gamachian) to probably earliest Silurian (part of the Rhuddanian). Cyclic sedimentation related to relative sea-level changes is suggested by the repetition of carbonate lithologies separated by marker beds that probably represent disconformities of uncertain duration. The late Rhuddanian brachiopod *Virgiana decussata* (Whiteaves) occurs at the base of the Interlake Group in the Williston Basin and in the Severn River Formation of the Hudson Bay Basin, indicating the probable connection of the two basins at that time. In northern Manitoba, conodont data clearly indicate that the type section of the Port Nelson Formation is entirely Late Ordovician (Richmondian) and is correlated with the Stonewall Formation in the Williston Basin. The name Port Nelson Formation is advocated to replace the name Red Head Rapids.

Osadetz, K.G., Kohn, B.P., O'Sullivan, P., Feinstein, S., Hannigan, P.K., Everitt, R.A., ***Gilboy, C.F.****, Bezys, R.K., and Stasiuk, L.D. (1998): Williston Basin thermotectonics: Variations in heat flow and hydrocarbon generation;* ***in*** *Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L. (eds.), Eighth International Williston Basin Symposium, Sask. Geol. Soc., Spec. Publ. No. 13, p147-165.*

Apatite fission-track (AFT) thermochronology and organic maturity data indicate spatial and temporal variations in the thermal history of the Williston Basin. Variations of oil windows are associated with crustal structure. Oil windows are elevated by ~750 m to ~1250 m and heat flow, as determined from maturity models, is at least 18% higher in the North American Central Plains Conductivity Anomaly than in adjacent regions. The persistent difference in heat flow between regions is attributed to crustal compositional changes originating during the Precambrian Trans-Hudson Orogeny. In the same region, some deduce that current geothermal gradients are still high. Analysis of apatite fission track (AFT) data indicates complicated temporal and geographical heat flow variations in the Williston Basin and on the adjacent Canadian Shield. On the Canadian Shield and in the thin wedge of peripheral Williston Basin strata, AFT data typically record a Late Precambrian epeirogeny followed by episodic Phanerozoic heating and cooling, the pattern of which corresponds to Williston Basin sedimentation history. Elsewhere the record of Late Precambrian cooling is obliterated by a resetting of AFT clocks during the Permian. The regions affected include both a basin central zone, with a radius of more than 300 km, where the Phanerozoic succession is more than 1500 m thick; and a linear zone at shallower depths, trending northwesterly from Yorkton to Lake Athabasca in Saskatchewan. The Permian thermal anomaly is intrinsic to the mechanism of Williston Basin subsidence, in that, in addition to the foregoing, it is associated with a major erosional event and originates in the basement. With geohistory constraints, the AFT models suggest Permian heat flows that were at least 184% of Mesozoic to present values. Neither the timing nor magnitude of this thermal event is considered by current tectonic models. Everywhere the pre-Mesozoic thermal history is partially to totally obscured by heating accompanying the Rocky Mountain Foreland sedimentation that extended beyond the Williston Basin onto the Canadian Shield. In most locations and strata the main stage of hydrocarbon generation began no sooner than latest Cretaceous to Early Tertiary time, although Permian heating has a significant potential to affect organic maturity histories in select locations and in lower parts of the Phanerozoic succession. The Deadwood Formation, which may be a source of a regionally significant, but poorly described hydrocarbon system, is predicted to have reached the main hydrocarbon generation stage during the Late Paleozoic, as a direct consequence of the Permian heating.

Pratt, B.R., Bernstein, L.M., and ***Haidl, F.M.*** *(1998): Upper Ordovician reef in Red River strata, subsurface Saskatchewan;* ***In*** *Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L. (eds.), Eighth International Williston Basin Symposium, Sask. Geol. Soc., Spec. Publ. No. 13, p26.*

A 2.8 m thick boundstone unit occurs at the base of the Lake Alma Member, Yeoman Formation (Upper Ordovician), in the LVR et al. Steelman 7-28-4-4W2 well. It overlies 0.4 m of laminated lime mudstone and fine-grained grainstone which in turn overlie 3.4 m of bioclastic rudstone rich in laminar and low-relief domal stromatoporoid-like fossils. The reef is capped by 0.8 m of lime mudstone and fine-grained grainstone.

The reef is thrombolitic, in that it consists of millimetre- to centimetre-sized, knob-like digits and crusts of microbial origin, which impart a mottled appearance to the core. This microbial framework is composed of variable proportions of clotted micrite and hemispheroids of laterally juxtaposed, radiating micrite-walled tubes attributable to Ortonella (or Cayeuxia). Many clotted micrite knobs exhibit a radial fabric, and their outer portions are locally laminated and therefore stromatolitic.

Locally common are undulating laminar and rarely columnar stromatoporoid-like fossils 0.5 cm thick and several centimetres wide. Intergrown or incorporated into the clotted micrite are horizontal meandering to loosely coiled tubular skeletons 0.5 to 1 mm wide of unknown affinity, micrite-walled, Terebella-like 'worm' tubes, rare Wetheredella (foraminifer?) and ramose bryozoans. In the matrix are abundant ostracods, scattered brachiopods, gastropods, crinoid ossicles and possible bivalves. Small cavities contain geopetal micrite peloids. Larger pockets and intercalated thin beds and laminae of lime mudstone exhibit multiple generations of Planolites burrows suggestive of increasing induration. Isopachous fibrous submarine cement is common. Replacive anhydrite is ubiquitous and the rock is dolomitized.

This framework composition is unique among Upper Ordovician reefs which tend to exhibit a more diverse biota. Somewhat similar frameworks are known from the Alpine Triassic and Mediterranean Miocene and point to a marine but somehow ecologically stressed environment. The reef points to a more complex arrangement of facies in the Red River succession than hitherto believed.

Roberts, R. Gwilym and ***Maxeiner, R.O.*** *(1999): The Anglo-Rouyn Deposit, La Ronge, Saskatchewan: A Besshi-type massive Sulphide deposit;* ***In*** *Ashton, K.E. and Harper, C.T. (eds.), MinExpo'96 Symposium – Advances in Saskatchewan Geology and Mineral Exploration, Sask. Geol. Soc., Spec. Publ. No. 14, p44-55.*

The Anglo-Rouyn deposit is on the northwest shore of Lac La Ronge, approximately 35 km northeast of La Ronge, Saskatchewan. Between 1966 and 1972, 1.7 million tonnes of ore with an average grade of 1.7 percent Cu, 1.2 g/t Au, and 5.5 g/t Ag were extracted from three orebodies of chalcopyrite, pyrite, pyrrhotite, magnetite, and trace amounts of sphalerite. The property consists of: 1) a northeast-trending, northwest-facing sequence of metabasaltic flows and tuffs, accompanied by greywacke-type metasediments; 2) overlying footwall rocks of calc-silicate gneiss, hornblende-plagioclase gneiss and laterally equivalent, gneissic magnetite iron formation; and 3) the ore zone rocks, which consist of the host quartz-hornblende-plagioclase gneiss and quartz-plagioclase gneiss in the hanging wall.

The rocks of the area have undergone three episodes of deformation. The first of these is the most significant, since it established the structural architecture of the region and coincided with the regional, amphibolite facies metamorphism. The units of the mine area are on the northwest limb of an antiform that closes to the southeast. Both regional- and property-scale structural evidence indicate that the units face, as well as dip, to the northwest. The Jepson Lake granite, a regional-scale, sill-like body, was intruded into the hanging-wall units before or during deformation.

Major and trace element whole rock geochemistry was used in association with the geological data to determine the protoliths of the gneissic rocks associated with the ore. The stratigraphic succession in the mine area records the history of a volcano-sedimentary package in a volcanic arc environment as it evolved from mafic volcanism and siliceous greywacke-type sedimentation into a basin in which both clastic and exhalative, chemical sediments were deposited. The exhalative component in the footwall rocks changed from carbonate-silica in the sediments overlying the mafic volcanics to iron oxide-carbonate in the sediments underlying the ore zone. The clastic component is similar in each unit and was derived from the underlying mafic volcanics, probably by a combination of near-surface, submarine alteration and sedimentary processes. The cupriferous sulphides of the Anglo-Rouyn ore immediately overlie the magnetite iron formation, and the maximum development of sulphides in the basin appears to be at the fringes of the iron oxide-rich sediment (the magnetite iron formation). The units of the ore zone (quartz-hornblende-plagioclase gneiss and quartz-plagioclase gneiss) signify a stage in the development of the volcanic-sedimentary basin when exhalative sedimentary processes dominated over clastic sedimentation. The rocks are believed to be isochemically metamorphosed, mixed clastic-exhalative sediments.

The Anglo-Rouyn is an exhalative deposit and several characteristics, listed below, point to its classification with Besshi-type massive sulphide deposits: 1) the metal content of the sulphide ore is Cu, ±Zn, Au, low Pb; 2) the association of the ore body with mafic volcanic rocks and greywacke sediments in a probable back-arc setting; 3) the sheet-like form of the sulphide units, and the absence of any evidence of focused discharge sites; and 4) the close association of the ore with a succession of exhalative-clastic sediments, in which silica-carbonate exhalite is widely dispersed and the sulphide ore is associated with the more restricted iron oxide exhalite (magnetite iron formation).

Rostron, B.J., Holmden, C., and ***Kreis, L.K.*** *(1998): Hydrogen and oxygen isotope compositions of Cambrian to Devonian formation waters, Midale area, Saskatchewan;* ***in*** *Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L. (eds.), Eighth International Williston Basin Symposium, Sask. Geol. Soc., Spec. Publ. No. 13, p267-273.*

Hydrogen and oxygen isotopic compositions of formation waters from the Williston Basin are reported from drill stem tests and produced waters for a stratigraphic section near Midale, southeastern Saskatchewan. Above the Prairie aquitard, the Birdbear and Duperow aquifers exhibit the highest δD (-17‰) and δ^{18}O (6.9‰) values known from the Williston Basin. They are substantially more D and ^{18}O enriched than formation waters from equivalent aquifers 160 to 360 km farther north and northeast in stratigraphic sections above three potash mines. Below the Prairie aquitard, the three deepest aquifers at the Midale site yielded lower δD and δ^{18}O values than the Birdbear and Duperow aquifers and are relatively uniform in isotopic composition down to the Precambrian basement. The new data, in conjunction with data from the literature, show that Williston Basin formation waters vary substantially in isotopic composition between aquifers in stratigraphic section and within the same aquifer regionally. These large isotopic variations reveal the potential of H and O isotopes in Williston Basin formation waters for tracing petroleum migration pathways and for fingerprinting sources of contaminant water encountered during drilling and production of hydrocarbons.

Sibbald, T.I.I. *(1999): Nicholson Bay Uranium-Gold-PGE Deposits;* in *Ashton, K.E. and Harper, C.T. (eds.), MinExpo'96 Symposium – Advances in Saskatchewan Geology and Mineral Exploration, Sask. Geol. Soc., Spec. Publ. No. 14, p139.*

Between 1953 and 1982, the Beaverlodge uranium district produced some 25 000 t of uranium metal from 17 main mines. The producing deposits, as well as numerous other radioactive showings in the area, are predominantly classical epigenetic vein-type pitchblende occurrences. Most are hosted by rocks of the metamorphic basement although veins are also present in rift-deposited immature clastics and alkalic basalts of the unconformably overlying Paleoproterozoic (1700 to 1800 Ma) Martin Group. Mineralization is also known in the younger Mesoproterozoic (1450 to 1700 Ma) mature sandstones of the Athabasca Group.

The epigenetic deposits can be divided into two groups, respectively showing simple and complex mineralogy. In the former, pitchblende is accompanied by brannerite, chalcopyrite, pyrite, galena and nolanite, and uranium by a simple suite of elements (Cu, Pb, Fe, V, and S). In the latter, pitchblende and thucolite are accompanied by arsenides, sulphides, selenides and native metals, and uranium by a diverse group of elements (Cu, Ni, Co, As, Pb, Fe, V, Y, Se, Ag, Au, and PGEs).

The association of uranium, gold, and platinum group metals was first described in 1955, but only more recently has exploration interest for the precious metals gained importance. Impetus was provided by: 1) discovery of a potentially economic zone of gold-platinum group metal mineralization, adjacent to the historically mined Coronation Hill uranium-gold deposit, in the South Alligator River Uranium Field (SARUF) in the Northern Territory of Australia, and 2) recognition that Coronation Hill and other deposits in the SARUF show many similarities of mineralogy and geological setting to complex pitchblende veins in the Beaverlodge district. The regional geological analogy is further enhanced by the undoubted resemblance of the nearby world-class unconformity-type uranium deposits of the Alligator River Uranium Field to those within the Athabasca Basin of Saskatchewan. Exploration around Nicholson has identified, adjacent to historic uranium prospects, more extensive zones of gold and platinum group metal mineralization than previously recognized (Nicholson #2 zone) and has also resulted in new discoveries (Quartzite Ridge).

Cryptic gold and platinum group metal mineralization occurs within alteration zones commonly adjacent to uranium veins of complex mineralogy. These zones are characterized by: 1) hematization, silicification, and talcification of host dolomitic marbles, diopsidic calc-silicates, and quartzites; 2) extensive fracturing; and 3) development of vugs containing euhedral quartz, specular hematite, and carbonates. There is a close spatial relationship to the sub-Martin Group and/or sub-Athabasca Group unconformities, and detailed field relationships and U/Pb (pitchblende) age data suggest mineralization after deposition of the Athabasca Group. Preliminary fluid inclusion studies from secondary euhedral quartz and carbonates from the altered/mineralized zones indicate fluids with temperatures in the range 150° to 200°C and high salinities. Similar fluids characterize the unconformity-type uranium mineralization of the Athabasca Basin.

The uranium-gold-platinum group metal deposits of the Beaverlodge district and SARUF represent a new type of low-temperature, hydrothermal precious metal mineralization. Their economic potential is as yet unknown, as is the exploration potential of the Paleo- to Mesoproterozoic sandstone basins to which they appear related.

Syme, E.C., Lucas, S.B., Zwanzig, H.V., Bailes, A.H., ***Ashton, K.E., and Haidl, F.M.*** *(1998): Geology, NATMAP Shield Margin Project Area, Flin Flon Belt, Manitoba/Saskatchewan accompanying notes; Geol. Surv. Can. Map 1968A, Manit. Energy Mines Map A-98-2, Sask. Energy Mines Map 258A, 54p.*

The regional compilation maps of the Paleoproterozoic Flin Flon Belt, southern Kisseynew Domain and interpreted sub-Phanerozoic basement (six sheets, 1:100,000 scale), and adjacent Phanerozoic cover (Fig. 1a, 1:325,000 scale), represent synthesis products stemming from the NATMAP Shield Margin Project. These maps are the culmination of efforts by the project partners (Manitoba Geological Services Branch (MGSB), Saskatchewan Geological Survey (SGS), and Geological Survey of Canada (GSC)) and build on the rich history of geoscience mapping in the Flin Flon Belt. A companion set of surficial geology maps has been produced at 1:100,000 scale (see below). A preliminary CD-ROM containing digital maps and an integrated geoscience knowledge base was released in 1993 (Broome *et al.*, 1993; Broome and Viljoen, in press). The final synthesis maps, more detailed maps, and most other geological, geophysical, and geochemical information sets pertinent to the project area are planned for release in digital format in a final project CD-ROM in 1999.

The National Geoscience Mapping Program (NATMAP) aims to foster a multidisciplinary team approach to bedrock and surficial mapping and related research, combine the efforts of federal, provincial and university scientists, and utilize digital information technology for more efficient interdisciplinary research and map publication. The Shield Margin Project, initiated in March 1991, was an inaugural NATMAP venture (Lucas *et al.*, in press a, b). Its purpose was to study the Paleoproterozoic rocks of the Flin Flon Belt and their continuation below gently dipping Paleozoic carbonates and the Quaternary cover. The region was chosen in part because of its economic significance: the Flin Flon greenstone belt is the largest Paleoproterozoic volcanic-hosted massive-sulphide (VMS) district in the world (e.g. Galley, 1996, and references therein), and also contains producing gold deposits.

The Shield Margin Project is closely tied to a variety of initiatives, including the Partnership Agreements on Mineral Development (1990-95) in Manitoba and Saskatchewan, the Snow Lake Exploration Technology (EXTECH) project, LITHOPROBE's Trans-Hudson Orogen Transect (THOT), the International Metamorphic Map program, and the Industrial partners Program (with Hudson Bay Mining and Smelting Co.). The NATMAP project team has brought together over 50 participants from government surveys, universities (Calgary, Saskatchewan, Regina, Manitoba, Queen's, Ottawa, UQAM, Concordia, McGill, UNB) and the minerals industry.

Yeo, G.M. *(1999): Is the Janice Lake unconformity a link between the Hearne Craton and the La Ronge–Lynn Lake volcanic arc?; Institute on Lake Superior Geology Proceedings, 45th Annual Meeting, Marquette, MI, 1999, v45, Part 1, p59-60.*

The Wollaston Domain, a NE-trending, 75 km wide belt of 2076-1860? Ma paragneisses, overlying Archean orthogneisses along the eastern edge of the Hearne Craton in Saskatchewan, is separated from 1910-1875 Ma arc volcanics and sediments of the La Ronge Domain by (a) Archean orthogneisses, poorly known supracrustal rocks, and minor Proterozoic plutons of the Peter Lake Domain, (b) 1855 Ma monzogranite to quartz diorite of the Wathaman Batholith, and (c) the Rottenstone Domain, a migmatitic belt of sediments, similar to those of the La Ronge Domain, intruded by tonalite. The boundary between Wathaman Batholith and Wollaston and Peter Lake domains is the Needle Falls–Parker Lake Shear Zone. While this is a fundamental break between ancient crust to the west and juvenile crust of Trans-Hudson Orogen to the east, there is no evidence that it is a collisional suture.

Within the Wollaston supracrustal succession, the Janice Lake Conglomerate, which can be traced discontinuously for 245 km along the eastern margin of the belt, marks a major unconformity. The conglomerate is polymictic, with clasts derived from underlying strata predominating. Locally, it includes fanglomerate. Although the conglomerate cannot be traced westward, younger calc-silicate bearing strata, locally resting on various older lithostratigraphic units, mark the presence of a profound unconformity. A correlative unconformity has been recognized in the Manitoba segment of Wollaston Domain, another 200 km to the northeast.

In the absence of any evidence for thermal uplift (i.e. igneous activity), uplift and extension in Janice Lake time must be due to mechanical flexure of the crust. A probable cause is tectonic loading of the eastern margin of the Hearne craton as the La Ronge–Lynn Lake volcanic arc converged towards it over an east-dipping subduction zone. Volcanism in the La Ronge–Lynn Lake arc began about 1910 Ma and reached a peak about 1880 Ma. Following arc-craton collision at about 1860 Ma, the sense of subduction was reversed and the Wathaman Batholith was emplaced at about 1855 Ma. Geochemical evidence suggests that the La Ronge segment of the arc developed in a transitional crust setting, close to or partly over marginal continental crust.

Tectonic loading of the outboard margin of the Hearne Craton would have resulted in an inboard flexural bulge, with consequent normal faulting and erosion over its crest and deposition of coarse clastics on its flanks. As convergence proceeded, the bulge would have migrated cratonward and died out, creating a diachronous regional unconformity. Preservation of coarse clastics would be favoured only on the trailing, eastern flank of the bulge, however. The approaching volcanic arc would have become a barrier to the open ocean, and accumulation of evaporites and carbonates in the resulting restricted basin would have been increasingly favoured.

This hypothesis also explains the dramatic change in sedimentation recorded by the Wollaston paragneisses. Following 2100 Ma rifting, the widespread Lower Sequence of psammopelites, pelites, and feldspathic psammites accumulated on a passive margin. As arc-craton convergence proceeded, coarse clastics were shed off a migrating flexural bulge ahead of the arc. Upper Sequence calc-silicate rich strata subsequently accumulated in the developing foreland basin.

Yeo, G.M. *(1999): Low-resolution sequence stratigraphy of early Proterozoic paragneisses, Wollaston Domain, Saskatchewan; Institute on Lake Superior Geology Proceedings, 45th Annual Meeting, Marquette, MI, 1999, v45, Part 1, p61-62.*

The Wollaston Domain is a NE-trending, 75 km wide belt of early Proterozoic paragneisses, overlying Archean orthogneisses along the eastern edge of the Hearne Craton; west of the Trans-Hudson Orogen. Bimodal volcanics near the base of the paragneiss succession give a U-Pb zircon age of 2.08 Ga, while minor gabbro and granitic plutons range from 1.81 to 1.84 Ga. A three-year, 1:20 000 scale mapping project was begun in 1997 in the southern part of Wollaston Domain to improve understanding of the stratigraphy and structure of the gneisses, which underlie the unconformity-type uranium deposits of Athabasca Basin. A basic strategy of the project is to map outward from Archean inliers so as to be able to work out the stratigraphic succession in spite of complex deformation and high metamorphic grade.

Four episodes of regional deformation can be distinguished. D1 involved isoclinal folding, local basement overthrusting, and transposition of primary layering into the S1 foliation. D2 involved tight to isoclinal folding about NE-trending axes, superposition of a strong S2 foliation, and local thrust faulting. D3 involved local open folding about SW to NW axes, and local brittle-ductile fault movement. D4 involved minor sinistral offset on a series of N to NNW trending brittle faults.

Two episodes of high T–low P (upper amphibolite–lower granulite facies) metamorphism are associated with D1 and D2 deformation. Peak P-T conditions, reached during D2, were about 750°C and 5 kbar. Along the eastern margin of the belt, however, metamorphic grades are relatively low (upper greenschist–lower amphibolite facies).

Two widespread paragneiss successions are distinguished in Wollaston Domain: a lower Pelite Unit, and an overlying Psammite Unit. These can be subdivided into at least eight subunits in the Foster–Daly lakes area. Two restricted successions are also recognized: a basal package (Courtenay Lake and Souter Lake Formations), preserved locally along the eastern margin of the domain, and the heterogeneous Hidden Bay Assemblage of interlayered quartzites, pelites, amphibolites, calc-silicates, and marbles, which likely overlies or is correlative with the Psammite Unit near Wollaston Lake. The Courtenay Lake Formation has been demonstrated to be a rift succession, while a passive margin setting is inferred for the overlying Pelite and

Psammite units. Attempts to determine the depositional setting of individual lithologic units, however, have been restricted to the low-grade rocks along the eastern margin of the domain.

Although sequence stratigraphy has become a standard technique for analysis of platform and craton margin strata, there have been few attempts to apply it to metamorphosed and deformed rocks. As demonstrated here, it has great potential in interpreting strata in which obliteration of primary features limits application of facies models or comparison with modern sedimentary environments.

Two major sequence boundaries subdivide the succession. The unconformity on Archean basement can be recognized without difficulty. The base of the Janice Lake Conglomerate (Unit Wo) marks a second unconformity. To the west, where the conglomerate is absent, this unconformity corresponds to the base of the calcareous rocks that overlie it. Within each sequence, the mapped lithofacies units can be assigned to a succession of systems tracts.

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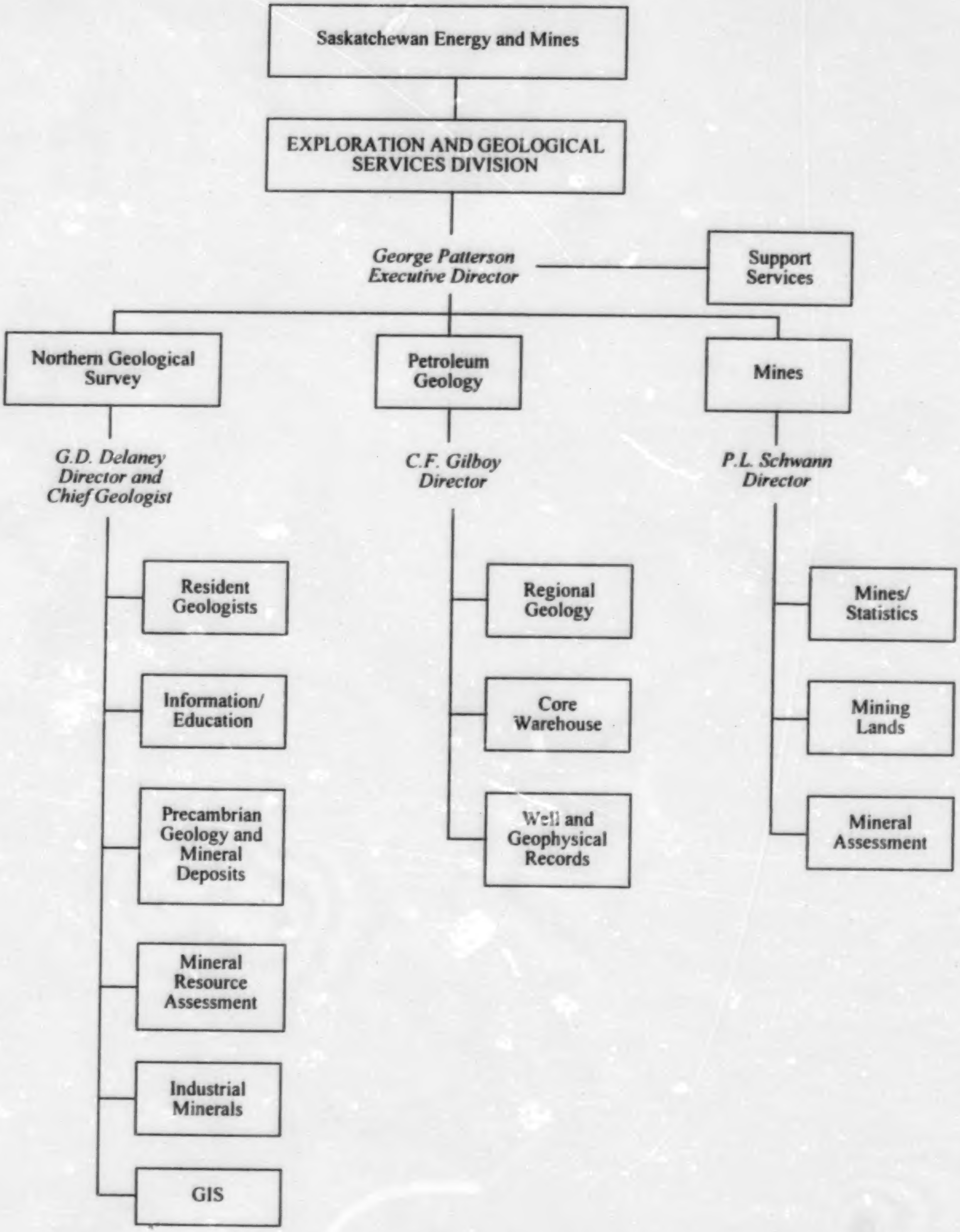

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